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SENSITIVITY ANALYSIS OF TRANSIENT AND STEADY STATE CHARACTERISTICS OF SURFACE SHIP PROGRESSIVE FLOODING

by

Timothy C. Spicer

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Thesis Advisor: Fotis A. Papoulias

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SENSITIVITY ANALYSIS OF TRANSIENT AND STEADY STATE CHARACTERISTICS OF SURFACE SHIP PROGRESSIVE FLOODING

Timothy C. Spicer
Lieutenant, United States Navy
B.S. Computer Science, United States Naval Academy1993

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Author: ______________________
Timothy C. Spicer

Approved by: ______________________
Fotis A. Papoulias, Thesis Advisor

____
M. D. Kelleher, Acting Chairman
Department of Mechanical Engineering

ABSTRACT

The Navy's primary analysis of damage control and stability to date has been under static conditions. Dynamic effects, such as progressive flooding, and the dynamic damage control procedures, such as hole patching and dewatering, have not been included in present design requirements. The goal of this thesis is to develop and test a stand-alone progressive flooding model. This model can be used to evaluate the transient and steady state characteristics of shipboard progressive flooding. Several improvements over previous studies are introduced and their effects are assessed. A sensitivity analysis study is performed through a systematic series of runs for a variety of hull forms. These results can be used to aid engineers of future ship designs in the use of damage control techniques and parameters.

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I. INTRODUCTION

A. BACKGROUND

Damage control practices are one of the most effective ways to increase ship survivability. Damage control practices can be categorized in two ways: static, such as the use of watertight bulkheads and other watertight fixtures and dynamic, such as the use of repair and dewatering techniques. Static damage control practices have been used for centuries as early shipbuilders designed watertight bulkheads into their design. Although it can not be documented it is suspected that the use of dynamic damage control procedures dates back even further since common sense dictates the use of dewatering and repair techniques on a damaged vessel. In the 1930's the U.S. Navy began, for the first time, implementing damage control and damage stability criterion into future ship design. After World War I the Navy began conducting damaged stability studies on new combatants. These studies led to some of the damage control practices implemented during World War II [Ref. 1]. Post World War II studies conducted by the Bureau of Ships, the current Naval Sea Systems Command (NAVSEA), resulted in the requirement that Naval vessels be able to withstand a hole that was equal to 15% of there length for combatants and 12.5% of there length for auxiliaries [Ref. 2].

B. CURRENT DESIGN REQUIREMENTS AND PROCEDURES

The current standards are delineated in NAVSEA Design Data Sheet 097-1 (DDS 097-1). These standards are based upon a study by T. H. Sarchin and L. L. Goldberg and the BuShip study of 1947. The DDS 097-1 criterion for compartmentation of category I ships (which includes combatants) is that the ship withstand a rapid influx of water from a shell opening equal to 15% of the ship's length at any point along the length of the ship. Reserve buoyancy requirements are that the equilibrium line not be above the margin line, which lies three inches below the main deck [Ref. 1]. The Navy currently uses a naval architecture program called the Ship Hull Characteristics Program (SHCP) as its primary tool to implement these requirements [Ref. 3]. This is a Fortran based program that uses a geometry interpreter and several naval architecture functions to evaluate the hull-form. This procedure is limited because it does not implement any dynamic damage control techniques such as dewatering or repair. This evaluation also does not take into account the effects of progressive flooding into adjacent compartments.

C. THESIS OUTLINE AND CONTRIBUTIONS

By the year 2010, the Chief of Naval Operations (CNO) has endorsed a series of operational characteristics that must be incorporated into surface combatants. One of the primary characteristics is that the ship must retain the ability to conduct combat operations, even though it has sustained hull damage and flooding [Ref. 1]. This requirement has further outdated the static damage control and stability tests that are

conducted with the SHCP. David Taylor Research Center has conducted dynamic damage control tests on certain surface combatants to evaluate their stability. Further dynamic testing of surface combatants is needed as the Navy shifts to more performance based requirements. This thesis designs a progressive flooding tool that will aid to further implement some of the operational characteristics of surface combatants. Some of the advantages and limitations of this progressive flooding simulation program are:

1. Visual Basic allows the development of a portable analysis tool that can be taken to any location that has a portable computer with a Windows 95/98/NT operating system. The simulation model can easily be installed on a portable computer in a matter of minutes and no supporting software is required.
2. Visual Basic allows the programmer of the analysis tool to include many of the graphical and visual features that further analyze transient and steady state characteristics of the progressive flooding process. Furthermore, these features are implemented in a familiar and user-friendly interface, which will keep the user learning curve at a minimum.
3. The user can conduct real-time damage control techniques and include them into the simulation, such as hole plugging and dewatering with installed pumps.
4. The user can decide what will be the limiting criterion for the progressive flooding simulation such as available freeboard and minimum transverse metacentric height.
5. The Visual Basic language allows the user to develop an accurate model, which includes all necessary naval architecture parameters. Extensions to include dynamics effects such as water sloshing are possible and can be easily

incorporated into the program. On the other hand, it will be rather cumbersome to include an accurate simulation of pump characteristics and the ship's fire main system. If such studies are needed, we recommend the use of a SIMSMART based tool [Ref. 1] that includes all necessary algorithms for solving a network of Bernoulli and continuity equations.

Chapter II of this Thesis presents the mathematical model that was utilized in the program. The basic flow-rate equations along with the fundamental naval architectural equations are presented for a rectangular barge, a Wigley hull, which is an analytical hull form explained in Chapter II, Section B, and an arbitrary hull form. The development and operation of the main simulation program are also described in this chapter. Chapter III presents results on program validation. This is accomplished by comparing the results for the Wigley hull with results obtained by treating the same hull as if it were an arbitrary hull with user-provided hydrostatic data. Based on the results of various simulation scenarios, several trends are identified and discussed. Finally, in Chapters IV and V, we summarize the main conclusions from this study and offer recommendations for further research.

II. DEVELOPMENT OF THE SIMULATION MODEL

A. APPROACH OF MODEL DEVELOPEMNT

The primary reason for development of this model is to analyze the transient and steady state characteristics of surface ship progressive flooding. When a hull form composed of various compartments suffers damage and becomes open to the sea the compartment that is open to the sea floods. If the damage was not severe and the watertight integrity remains intact then the flooding is isolated to only that compartment. However, it is more realistic to consider the damage severe enough to disrupt the watertight integrity of that compartment and introduce progressive flooding into the surrounding compartments through small holes or fragmentation. Progressive flooding may also occur due to improper maintenance or normal wear and tear of watertight fixtures. It can eventually become serious enough to cause the ship to founder (sinking caused when the remaining buoyancy is less than the ship's weight) or the ship can capsize due to loss of stability.

The main focus of this model will be on three compartments. The user will define the bulkhead locations at the beginning of the simulation. The primary compartment will contain the hole(s), which open it to the sea and allow it to flood. This compartment can have as many as two holes open to the sea. The user will define the diameter, height and flow coefficient of all holes at the beginning of the simulation. Default values for the flow coefficients (equal to 0.7) are provided by the program. The two additional compartments will be called secondary compartments. They are located immediately

forward and aft of the primary compartment. The secondary compartments can contain as many as three secondary fragmentation holes, which allow the primary compartment to progressively flood into the secondary compartments.

The model for this analysis was developed using the Microsoft Visual Basic programming language. One of the main goals for this thesis was to develop an analysis tool that was independent of any other programs. It was also desirable for the analysis program to be easily exportable so that it may run on other platforms. Visual Basic is an excellent tool for developing stand-alone, exportable programs. Once a program is developed it can be compiled into an exportable package that can be easily installed on any desktop computer. Visual Basic also offers the programmer access to some of the mouse driven visual features common in most modern programs, allowing the end user of the analysis program to demonstrate a real-time, interactive scenario. Some of the real-time features, which are included in this simulation tool, are hole clogging (or repair) and additional pumping to aid in the dewatering process.

The user can use this program to monitor various aspects of shipboard progressive flooding. Some of the parameters of interest are metacentric height ($\overline{GM}$), available freeboard, and trim forward and aft. The $\overline{GM}$ is a measure of the ship's transverse stability and can be continuously observed while the simulation is running. A significant decrease in $\overline{GM}$ may allow the ship to capsize when a list is encountered. The available freeboard can also be continuously monitored while the simulation is running. The available freeboard is a measure of the reserve buoyancy that the ship has at an instant in the simulation. When the freeboard is depleted the ship will founder. The trim that the ship experiences during the simulation may be of interest to the user if the hull has certain

trim restrictions. The simulation will automatically terminate when the simulation reaches a user defined minimum $\overline{GM}$ or all available freeboard has been depleted. All simulations in this version are performed using an explicit Euler's formula, which is adequate for the time scales considered. In case more elaborate effects are required, such as compartment water sloshing, the method can be easily changed into a Runge-Kutta based formula.

B. HULL FORMS USED FOR THIS ANALYSIS

The program was developed allowing the user to choose from three hull forms to run the analysis. The three hull forms are: a basic barge (rectangular hull form), the analytical Wigley hull form, and a file containing the data of an existing hull form.

The barge hull form is used as a demonstration tool for the program. The rectangular barge will have the dimensions L (length), B (Beam), T (draft), and H (height). The rectangular shape allows the programmer to develop a simple model, which can be verified with hand calculations. The user must define all of the necessary dimensions at the beginning of the simulation.

The Wigley hull form used in the development and testing of the program is shown in (Figure 2.1). It was chosen due to its ease of analytical representation. The offsets of the Wigley hull are described by the following equation.

$$y = \frac{B}{2}\left(1 - \frac{(T-z)^2}{T^2}\right)\left(1 - 4\frac{x^2}{L^2}\right) \qquad (1)$$

Where:

x = longitudinal distance from midships

y = transverse distance from centerline

z = height above keel

B = beam (maximum)

T = draft (maximum)

L = length between perpendiculars

This equation for the offsets can be manipulated analytically to derive all of the necessary equations to model flooding in this hull. The choice for the rectangular barge and Wigley hull forms, besides the obvious advantages of ease of analytical representation, offers another feature, which is proven very useful in the parametric studies. The barge is a perfectly wall-sided hull form whereas the Wigley hull shown in (Figure 2.1) offers a monotonically increasing flare throughout the range of its length. As a result it has a significantly higher stiffness in transverse motions. The two hulls can be viewed as rather extreme cases, which means that in a qualitative sense, results obtained for realistic hull forms are expected to lie between these two cases.

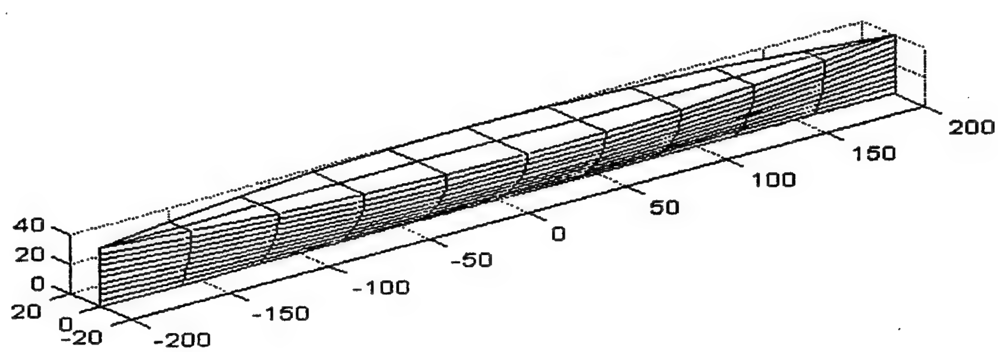

Figure 2.1 View of Wigley Hull

The third hull form will be a more specific user supplied hull. The user must supply four files containing the necessary stability parameters to run the simulation. One file will contain data for the main hull and the other three files will contain data for the three flooded compartments. All four files must be saved in a comma delimited format (CSV) and must be ordered such that draft or compartment volume increases until file termination. The hull data file must contain six columns of data, where each column respectively represents the draft, volume, tons per inch immersion, vertical distance of the center of buoyancy above the keel, and the transverse and longitudinal metacentric radii. Each of the compartment data files must be formatted with seven columns that respectively represent water level, volume, vertical center of gravity, transverse moment of inertia, longitudinal moment of inertia, surface area and longitudinal center of gravity. This option gives the user the capability to simulate any hull form that has the necessary parameters available. For the purpose of program testing and comparison four Matlab M-files listed in (Appendix A) were used to generate four files using the analytical Wigley equations. A sample of the data generated for the Wigley hull is listed in (Appendix B) and a sample of the data for a compartment in the Wigley hull is listed in (Appendix C).

C. FLOW RATE THROUGH HOLES

Holes can be modeled as a short-tube orifice with the diameter (hole size) much larger than the tube length (hull thickness). This enables the flow through these holes, either primary or secondary flooding, to be modeled as turbulent flow through an orifice of negligible length. The flow rate then becomes a function of the hole size, the hole

shape and the pressure difference across the hole. The hole shape is used to derive a discharge coefficient C_d. The coefficient, C_d, is supplied by the user at the beginning of the simulation. A C_d of 0.7 is supplied as the default value based upon predictions for a sharp edged hole [Ref. 4]. The equation for flow through the hole can be described by the following equation.

$$Q = C_d * A * \sqrt{2 * g * \Delta h} \tag{2}$$

Where:

Q = flow rate

A = cross-sectional area of the hole

C_d = discharge coefficient

g = gravitational constant

h = the height of fluid on each side of the hole

The difference in height of the flooding water on each side of the hole will depend on the draft of the ship, trim of the ship (for both exterior water and tank levels) and the level of flooding water inside the compartment. In the progressive flooding calculations, equation (2) is in reality a set of equations and are implemented as follows:

- First, the flow rate for each hole in each compartment is calculated using equation (2). The square root indicated in the equation, is a signed square root, in other words the square root of the absolute value of the head difference Δh divided by the sign of Δh. In this way, the value of Q is either positive (indicating net inflow into the compartment) or negative (indicating net outflow from the compartment) as it should.

- The head difference Δh depends on the height of the water inside the compartment which is calculated by applying the incompressible flow continuity equation $\sum Q = A_C \dot{h}_C$. In this equation, the sum on Q contains all inflows and outflows from each compartment including pumping rates, A_C is the plan form area of the compartment at the indicated height, and h_C is the water height inside the compartment.
- The head difference also depends on the relative position of the damage hole with respect to the compartment water level and the seawater level outside the hull. The latter depends on the ship's draft and trim, which are calculated as shown in the following section. The ship's trim also affects the water height between adjacent compartments. This trim effect, although relatively small, has been incorporated in the simulation program.

D. NAVAL ARCHITECTURE EQUATIONS

Regardless of the type of hull-form chosen to simulate there are numerous stability parameters that are common to the three hull-forms and these parameters must be calculated to simulate the overall effect on stability. Each of the parameters will be described below in the order, which they were solved in the model. The computational process for each parameter will be explained for each hull-form.

1. The Distance of the Center of Buoyancy Above the Keel ($\overline{KB}$)

Formally this value can be calculated with the expression

$$\overline{KB} = \frac{M_{\nabla K}}{\nabla}, \tag{3}$$

where $M_{\nabla K}$ is the total moment of the displaced volume and ∇ is the displaced volume [Ref. 5: p.44]. For barge calculations this is always

$$\overline{KB} = \frac{T}{2}. \tag{4}$$

For the Wigley hull equation (3) must be solved analytically. The value for the total moment of the displaced volume must be solved using the expression

$$M_{\nabla K} = \int Z dv, \tag{5}$$

which equates to

$$M_{\nabla K} = \int_{x_L}^{x_H}\int_{0}^{z_H} B\left(1 - \frac{(T-Z)^2}{T^2}\right)\left(1 - \frac{4X^2}{L^2}\right) Z dz dx, \tag{6}$$

where x_L, x_H are the limits of integration in the longitudinal direction, z_H is the limit of integration in the vertical direction, Z is height above the keel, L is length between perpendiculars and T is draft. The displaced volume of the Wigley hull, which will be used for numerous calculations equates to the analytical form

$$\nabla = \int_x\int_y\int_z dy dz dx. \tag{7}$$

Which simplifies to

$$\nabla = B\left(\frac{z_H^2}{T} - \frac{z_H^3}{3T^2}\right)\left(x_H - x_L - \frac{4}{3}\left(\frac{x_H^3}{L^2} - \frac{x_L^3}{L^2}\right)\right). \tag{8}$$

As computed the displaced volume will be in units of ft^3. The volume can be converted to displaced weight by using the equation

$$\Delta = \frac{\nabla ft^3}{35\frac{ft^3}{LT}}, \tag{9}$$

where Δ is the displaced weight in long tons. Using the above equations (3), (6) and (8) $\overline{KB}$ simplifies to

$$\overline{KB} = \frac{\left(\frac{2z_H^3}{3T} - \frac{z_H^4}{4T^2}\right)}{\left(\frac{z_H^2}{T} - \frac{z_H^3}{3T^2}\right)}. \tag{10}$$

For the user supplied hull form both the value of $\overline{KB}$ and ∇ must be given as a function of draft (T) or simplified as $\overline{KB}(T)$ and $\nabla(T)$.

2. Transverse Metacentric Radius ($\overline{BM}$)

Formally this value can be calculated by

$$\overline{BM} = \frac{I_T}{\nabla}, \tag{11}$$

where I_T is the transverse moment of inertia of the area at the waterline [Ref. 5:p. 84]. For the barge the simplifies to

$$\overline{BM} = \frac{B^2}{12T}, \tag{12}$$

where B is the beam and T is draft. For the Wigley hull the value I_T is needed. I_T can be calculated from the relation

$$I_T = \int\int x^2 dA, \tag{13}$$

which simplifies to,

$$I_T = B^3\left(1-\frac{(T-z_H)^2}{T^2}\right)^3\left[x - Ax^3 + \frac{3}{5}A^2x^5 - \frac{1}{7}A^3x^7\Big|_{x_L}^{x_H}\right]. \tag{14}$$

Where $A=4/L^2$ and x_H, x_L are the limits of integration in the x (longitudinal) direction. With both I_T and ∇ calculated equation (11) can be used. The user supplied hull form will contain the relation $\overline{BM}(T)$.

3. Tons Per Inch Immersion (*TPI*)

This value defines the number of tons of additional weight added that is required to submerge the hull one additional inch. This value can be calculated from the expression

$$TPI = \frac{A_w}{420}, \tag{15}$$

where A_w is the area of the waterline [Ref. 5:p. 46]. For the barge the value simplifies to

$$TPI = \frac{L*B}{420}. \tag{16}$$

For the Wigley hull A_w must be calculated before *TPI* can be solved. The calculation for A_w assumes the analytical form

$$A_w = \int_x\int_y dydx = 2\left(\frac{B}{2}\right)\left(1-\frac{(T-Z)^2}{T^2}\right)\left(x_H - x_L - \frac{4}{3}\left(\frac{x_H^3}{L^2}-\frac{x_L^3}{L^2}\right)\right). \tag{17}$$

With A_w calculated equation (15) can be used to solve for *TPI*. The user supplied hull form will contain the values *TPI(T)*.

4. Compartment Volumes (∇_c)

The flooded volumes, of each of the compartments, as flooding progresses needs to be computed. For the barge hull this computation is simply

$$\nabla_c = l * b * h, \tag{18}$$

where l and b are the length and breath of the compartment and h is the height of water in the compartment. To compute this for the Wigley Hull equation (7) was used with the values of the integration along x equal to the forward and aft bulkheads of the compartment. For the user supplied hull type the values of $\nabla_c(h)$ must be given.

5. Parallel Sinkage (*PS*)

With the displaced weights of each of the compartments previously calculated the parallel sinkage of the hull due to flooding can be found by using the expression

$$PS = \frac{\sum \Delta_c}{TPI}. \tag{19}$$

This expression can be used for all three hull types using the calculated or supplied compartment volumes.

6. Vertical Height of the Center of Gravity Above the Keel ($\overline{KG}$)

For all hull types an initial $\overline{KG}$ must be given to start the stability calculations. With the initial $\overline{KG}$ given, the change to $\overline{KG}$ can be calculated using the following formula

$$\overline{KG} = \frac{\left(\overline{KG_0} * \Delta_0\right)\left(\sum \Delta_c * \overline{kg_c}\right)}{\Delta}. \tag{20}$$

For this calculation the vertical center of gravity for each flooded compartment must be calculated. For the barge that value is

$$\overline{kg_c} = \frac{h}{2}, \tag{21}$$

where h is the height of water in the flooded compartment. For the Wigley hull the center of gravity of each compartment can be calculated using the expression

$$\overline{kg_c} = \frac{\int z dv}{\nabla_c}, \tag{22}$$

which simplifies to

$$\overline{kg_c} = B\left(\frac{2z_H^3}{3T} - \frac{z_H^4}{4T^2}\right)\left(x_H - x_L - \frac{4}{3L^2}\left(x_H^3 - x_L^3\right)\right)\left(\frac{1}{\nabla_c}\right). \tag{23}$$

For the user supplied hull form the value $\overline{kg_c}(T)$ must be given in the data file. Once the values of each compartment center of gravity are found equation (20) can be used to find the entire hull center of gravity.

7. Free Surface Correction (*FSC*)

When a compartment floods there is a virtual rise in the weight of the liquid in the compartment due to the free surface of the liquid. This virtual rise produces a virtual moment of free surface equal to the product of the weight of the liquid in the tank and its virtual rise. This moment of free surface affects the transverse stability of the ship by decreasing the ship's ability to right itself. The free surface correction can be calculated as follows,

$$GG_V = \frac{i_t}{\nabla}\left(\frac{\delta_S}{\delta_c}\right), \tag{24}$$

where i_t is the transverse moment of inertia of the compartment, δ_s is the density of the fluid that the ship floats in and δ_c is the density of the fluid in the compartment. The

transverse moment of inertia must be calculated for each flooded compartment. The general form for a rectangular transverse moment of inertia is

$$i_t = \frac{lb^3}{12} ft^4, \tag{25}$$

where l is the length of the compartment and b is the beam of the compartment. For the barge equation (25) can be used directly to solve for i_t. For the Wigley hull equation (14) can be used to find the i_t of each compartment by changing the values of integration along the longitudinal (x) direction to match the values of the forward and aft bulkhead in each compartment. The combined free surface correction is the sum of the free surface correction terms for each compartment expressed as

$$FSC = \sum gg_v , \tag{26}$$

where gg_v is the free surface correction terms for each compartment.

8. Metacentric Height ($\overline{GM}$)

The righting arm of a ship, $\overline{GZ}$, is a measure of a ship's ability to right itself when it experiences heel. $\overline{GZ}$ can be calculated from the formula

$$\overline{GZ} = \overline{GM} \sin\phi , \tag{27}$$

where ϕ is the angle of heel. Equation (27) is not used in the simulation since the model does not experience an angle of heel, therefore the metacentric height is used as a direct measure of the ship's ability to right itself. The metacentric height is calculated from the following equation for all three hull forms

$$\overline{GM} = \overline{KB} + \overline{BM} - \overline{KG} - FSC , \tag{28}$$

equations (3), (11), (20) and (26) are used for this calculation. The user can predetermine a minimum value for $\overline{GM}$ that will terminate the simulation, signifying a catastrophic loss of stability.

9. Longitudinal Metacentric Radius ($\overline{BM_L}$)

The understanding of the effects of trim and the definitions associated with trim is essential, before attempting to determine the changes in draft that results from the addition of weight, that occurs during flooding. The longitudinal metacentric radius is derived the same as the transverse metacentric radius, by integrating longitudinally to obtain the volumes and moments of volumes of the emerged and immersed wedges [Ref. 5:p. 137]. The formal equation for the longitudinal metacentric radius is

$$\overline{BM_L} = \frac{I_L}{\nabla}, \tag{29}$$

where I_L is the longitudinal moment of inertia of the waterplane. For the Barge hull form this calculation takes the form

$$\overline{BM_L} = \frac{L}{12 * T}. \tag{30}$$

For the Wigley hull form I_L must first be found. I_L equates to

$$I_L = \iint x^2 dA, \tag{31}$$

which simplifies to

$$I_L = B\left(1 - \frac{(T - z_H)^2}{T^2}\right)\left(\frac{x_H^3}{3} - \frac{x_L^3}{3} - \frac{4}{5L^2}\left(x_H^5 - x_L^5\right)\right). \tag{32}$$

Once I_L is found equation (29) can be used to solve for $\overline{BM_L}$. For the user supplied hull for the relation $\overline{BM_L}(T)$ must be given.

10. Longitudinal Free Surface Correction (FSC_L)

The longitudinal free surface correction must be calculated for all flooded compartments. Equations (24) and (26) can be used for this calculation if i_t for each compartment is replaced with the correct longitudinal calculation i_l.

11. Longitudinal Metacentric Height ($\overline{GM_L}$)

The longitudinal metacentic height for all three hull forms can be calculated from the following expression.

$$\overline{GM_L} = \overline{KB} + \overline{BM_L} - \overline{KG} - FSC_L \tag{33}$$

12. Moment to Change Trim One Inch ($MT1$)

The moment to change trim one inch is a convenient quantity to calculate because it is independent of trimming moment and it can be precalculated and treated as a property of the hull form. The property $MT1$ can be calculated from the following expression for all three hull forms.

$$MT1 = \frac{\Delta GM_L}{12L} \tag{34}$$

E. SIMULATION PROGRAM OPERATION

When first entering the simulation program the main run time screen will appear as shown in (Figure 2.2).

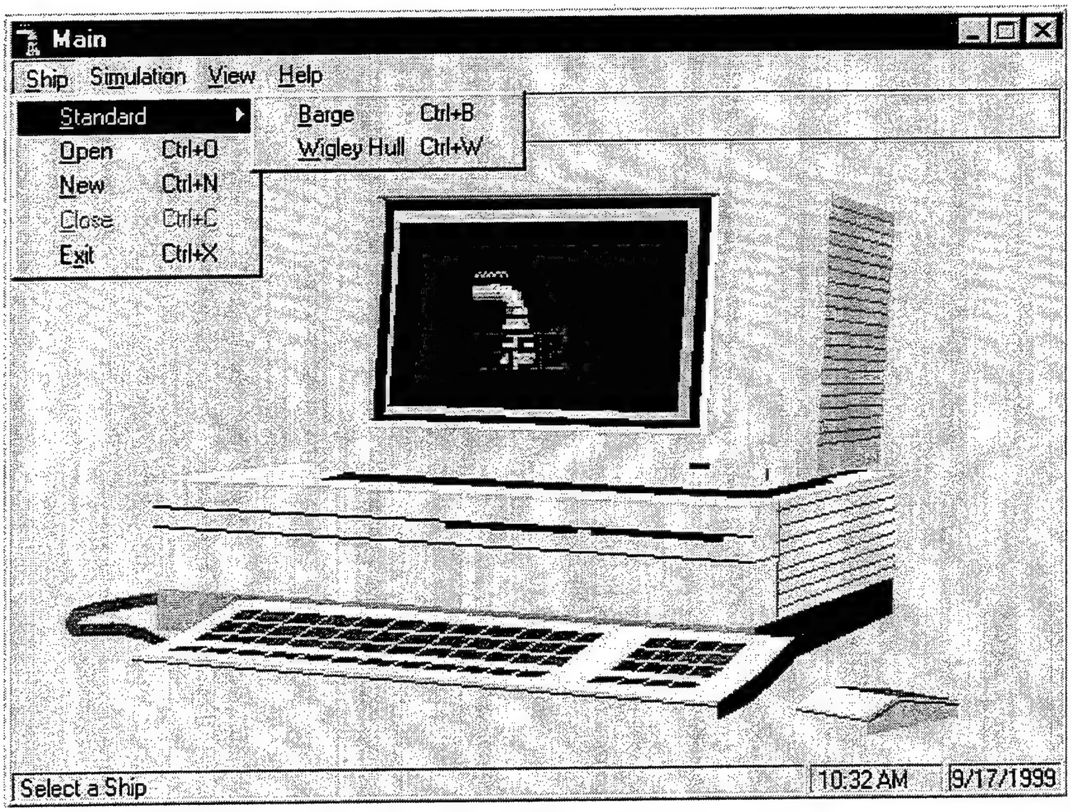

Figure 2.2 Run Time Environment Screen

This screen will give the user the option to choose which hull form is desired to run the simulation. The status bar provides the user with hints for follow-up actions. From the tool bar at the top of the screen one of the three available hull forms must be chosen. Some of the menus and buttons on the toolbar are disabled until a hull form is selected. When a hull form is chosen the simulation data screen will appear on the as shown in (Figure 2.3).

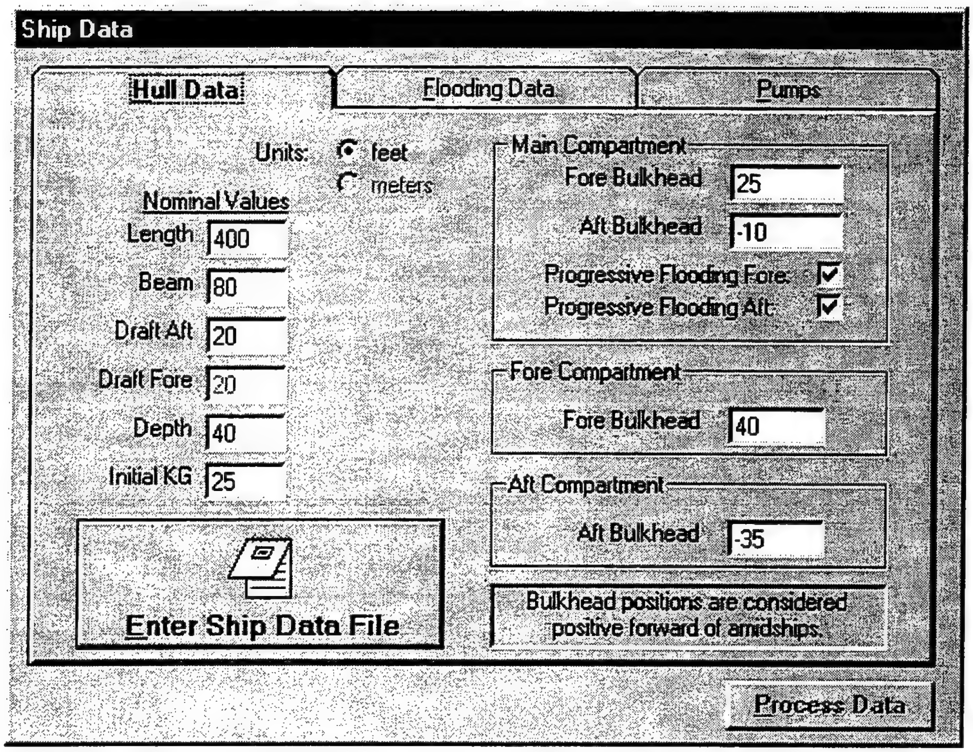

Figure 2.3 Simulation Data Screen

The simulation data screen prompts the user to enter the data necessary to simulate the flooding process. The user should select from one of the three tabs across the top of the screen. The hull data tab should be used to enter the specific hull and compartment dimensions such as length, beam, height, and bulkhead locations. The user must also enter the initial $\overline{KG}$ to start the stability calculations. If a user supplied hull form is being simulated the user will be prompted to enter the four files as shown in (Figure2.4).

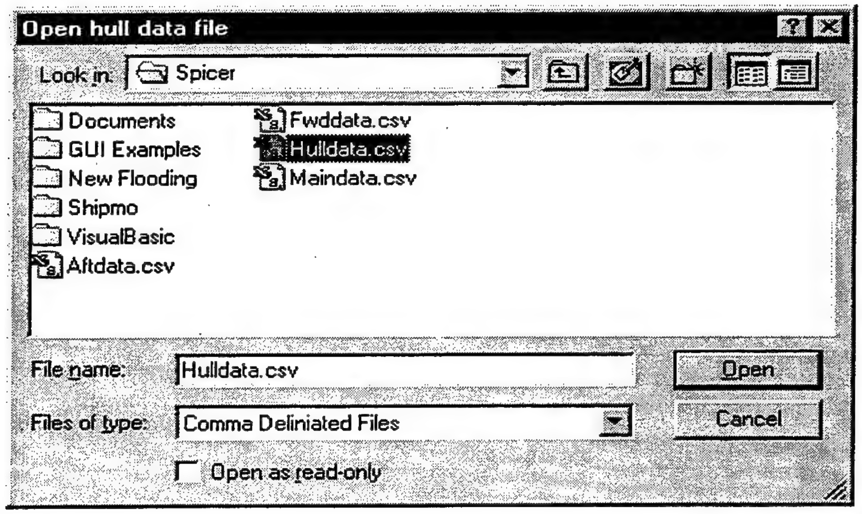

Figure 2.4 Data Files Input Screen

In the case of the rectangular barge or the Wigley hull, these "open dialog boxes" do not appear. When the flooding data tab is selected the user must enter the data necessary to simulate the flooding process. The data for all holes is entered on this form as shown in (Figure 2.5). All units in this version of the program are in feet. Hole data include the height above the keel, hole diameter, its longitudinal position measured forward of the aft bulkhead (main compartment only), and discharge coefficient C_d. Since roll dynamics are not incorporated in this version of the program, the transverse locations of the holes in the secondary compartments are not required. A maximum of two main damage holes and three fragmentation holes in each compartment is assumed.

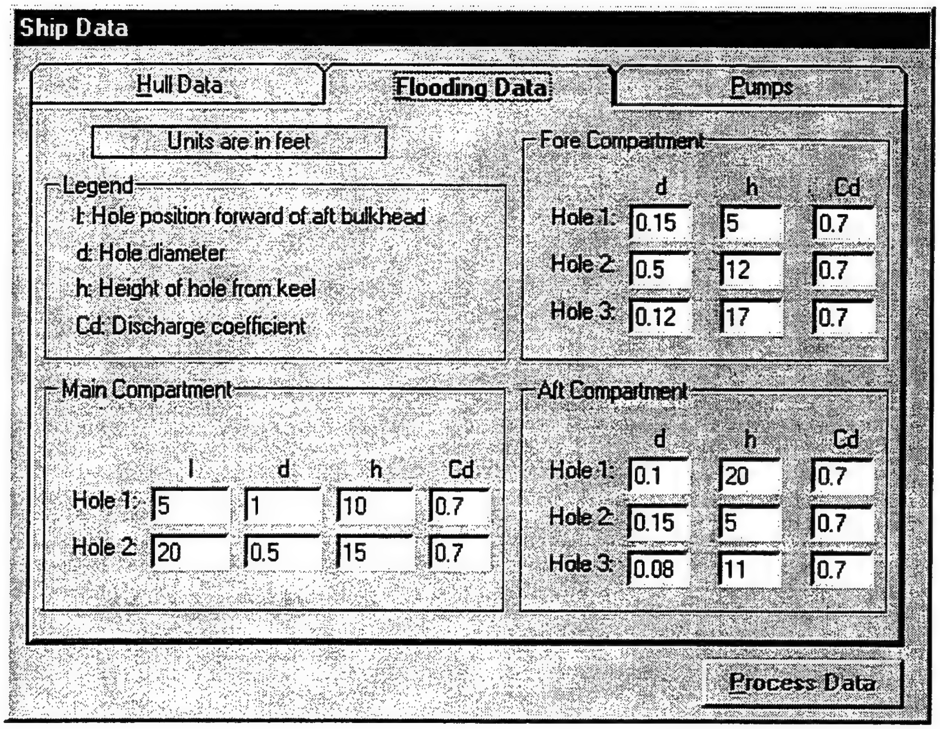

Figure 2.5 Flooding Data Input Screen

When the pumps tab is selected the user can input the data necessary for dewatering as shown in (Figure 2.6).

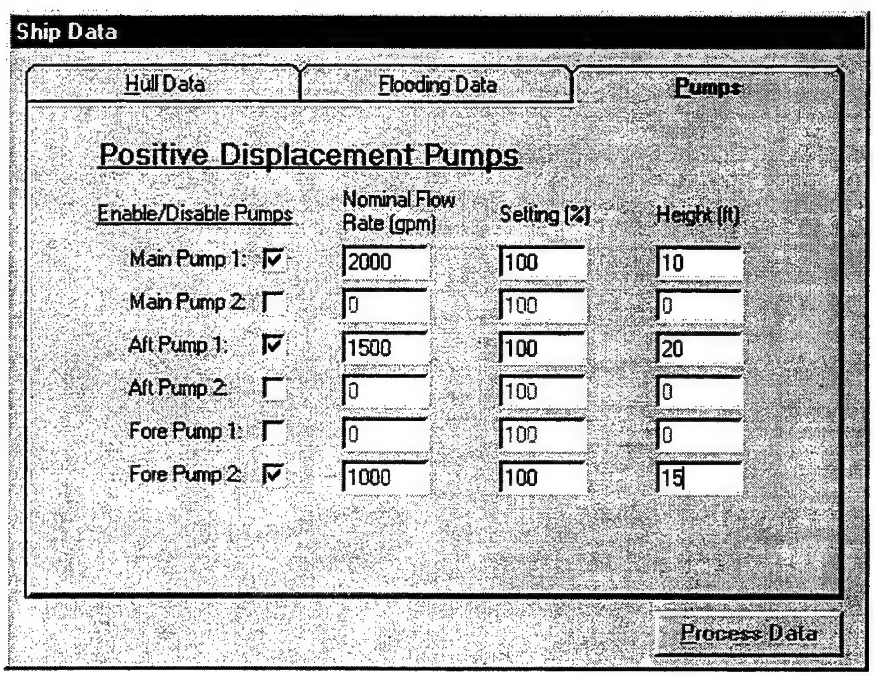

Figure 2.6 Pumps Data Input Screen

A maximum of two positive displacement pumps can be simulated in each compartment. The user must enter the necessary data such as pumping rate in gallons per min (GPM) and vertical location. After the simulation data has been entered the user will be prompted by the run time environment screen shown in (Figure 2.2) to enter the simulation parameters by selecting the simulation parameters tool button at the top of the screen. After clicking the simulation parameters tool button the simulation parameters screen will appear as shown in (Figure 2.7).

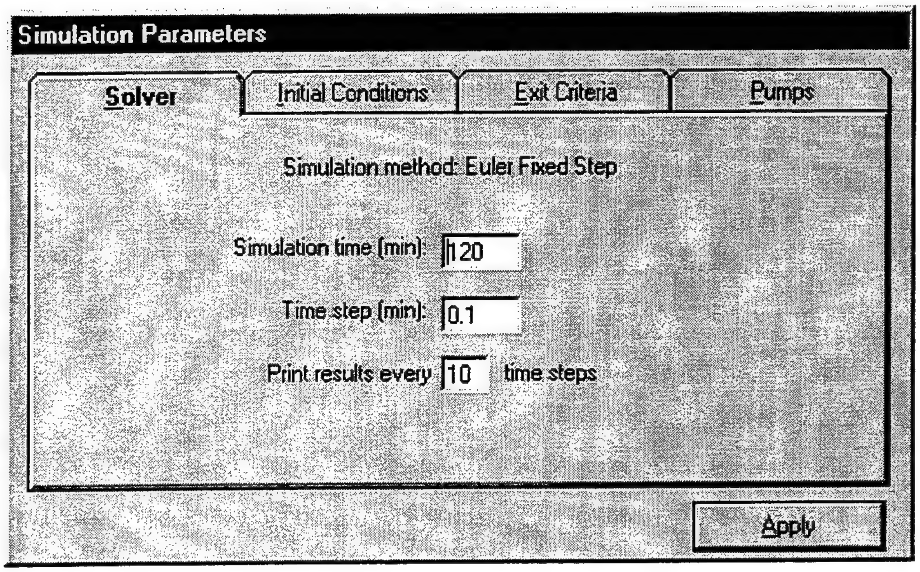

Figure 2.7 Simulation Parameters Screen

The user will have the option of selecting between four tabs across the top of the screen. The solver tab will allow the user to enter the parameters used by the Euler fixed step differential solver used in the simulation. Euler's method was chosen for its simplicity and because it is accurate for the time scales involved in the problem. The duration of the simulation can be entered along with the time step used. A typical time step of 0.1 minutes was determined to produce accurate results. The initial conditions

screen, shown in (Figure 2.8) can be used to regulate an existing water level in the three compartments. It should be mentioned that entering an arbitrary water level is not allowed in this version of the program and the corresponding text boxes shown in the figure do not accept user input. The reasons for this is that a non-zero water level should be consistent with the ship's draft and trim and before the simulation starts, no cross check is done by the program. The initial conditions screen can be refreshed if the user wishes to continue on a simulation that has ended. In this case the final water levels and the ship's draft and trim are used as initial conditions for the next simulation. The time index is also adjusted to account for simulation continuation in this case.

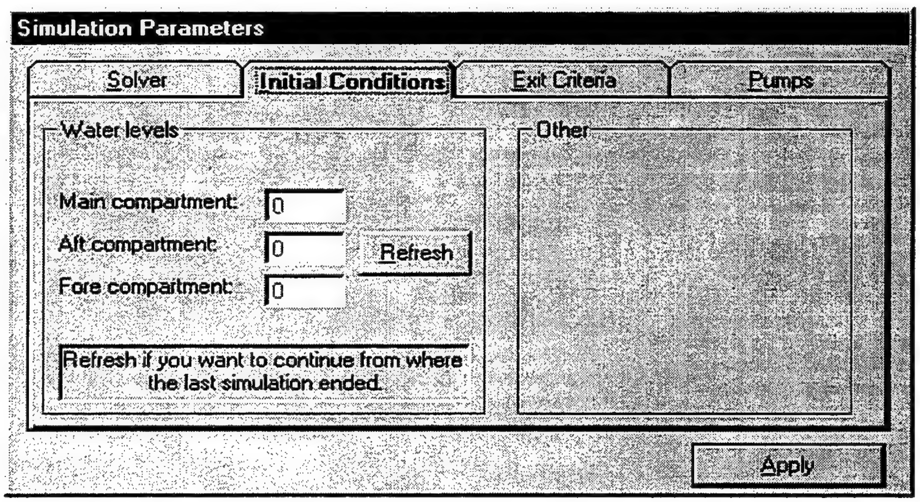

Figure 2.8 Initial Conditions Screen

The exit criterion screen, shown in (Figure 2.9), allows the user to enter what parameters, if any, may force simulation termination. The user has the option to choose between available freeboard and metacentric height. These values are continuously monitored during the simulation process. Simulation is terminated if any of these two minimum values are violated. The pump tab is for future model development

incorporating pump automatic control logic and has not yet been incorporated in the simulation process. All pumping actions in this version are manually controlled through the run time environment screen that is discussed below.

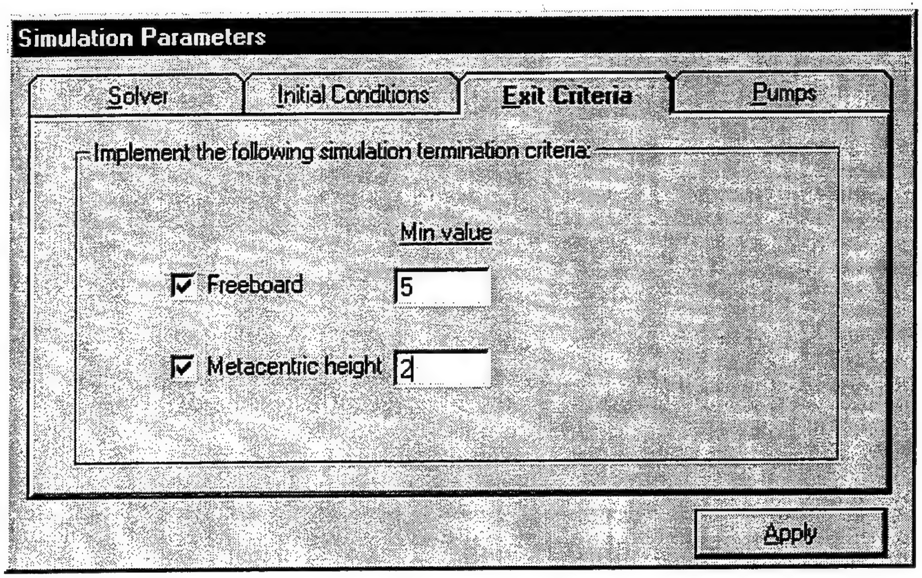

Figure 2.9 Exit Criterion Screen

When the simulation parameters have been the entered the user will be prompted to select a file to save the simulation results. This file can be used within the simulation program to graph the results or it can be exported in a comma separated values (CSV) format, which is compatible with most spreadsheet programs. After the file has been selected the main simulation screen will appear as shown in (Figure 2.10). The user must click on the run button located at the toolbar to begin the simulation. A progress bar depicts schematically simulation time progress. Also shown are the water levels in the tanks, and the ship waterline. Although these are depicted as square, the correct geometry as entered is used in the calculations. Damage and fragmentation hole locations and heights are also shown. The user may conduct real time damage control

operations using the hole clogging and pumps tabs (Figure 2.11) at the bottom of the screen. Hole diameters as well as pump heights and settings can be continuously adjusted and observed during simulation.

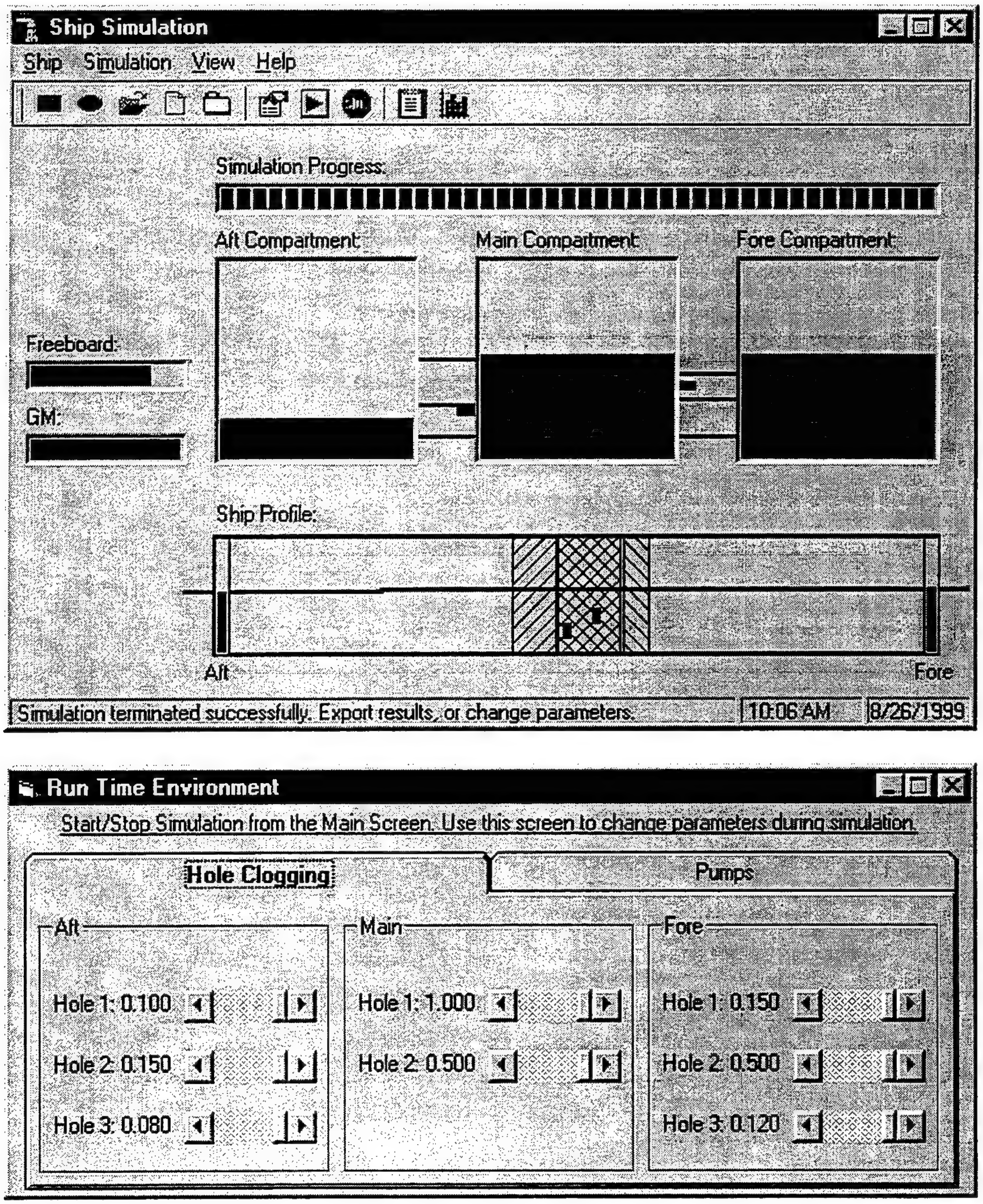

Figure 2.10 Main Simulation Screen

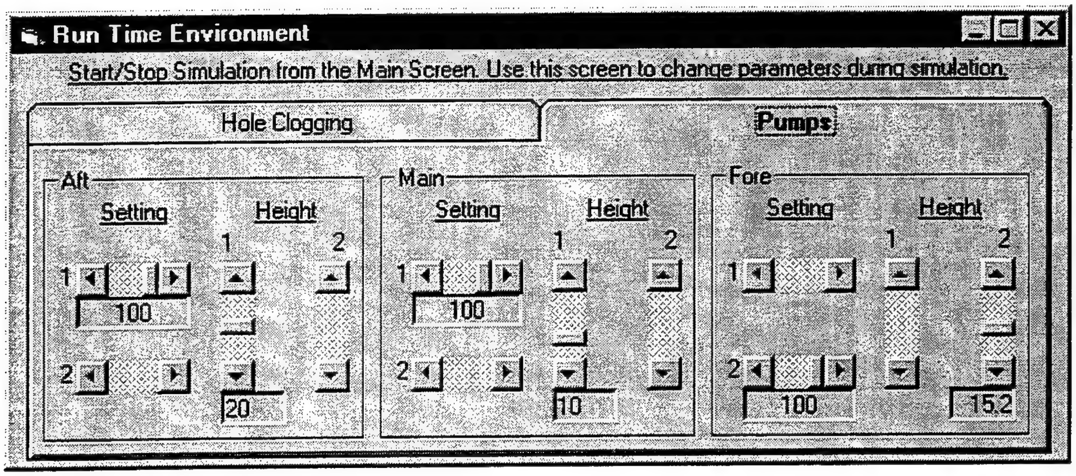

Figure 2.11 Pumps Manipulation Screen

The user can monitor progress of the simulation by watching various continuous updates on the screen including the water level in each compartment, the simulation time, draft forward and aft, available freeboard and available $\overline{GM}$. After successful program termination the user will have the options to continue the simulation, export the data in comma separated format, or graph the results. All main results can be also presented in graphical forms using the program's built-in graphical capabilities. A sample graph of the water depth of all compartments at simulation termination is shown in (Figure 2.11). These results (both in raw data or graph) can be copied into the Windows clipboard and pasted into any other application.

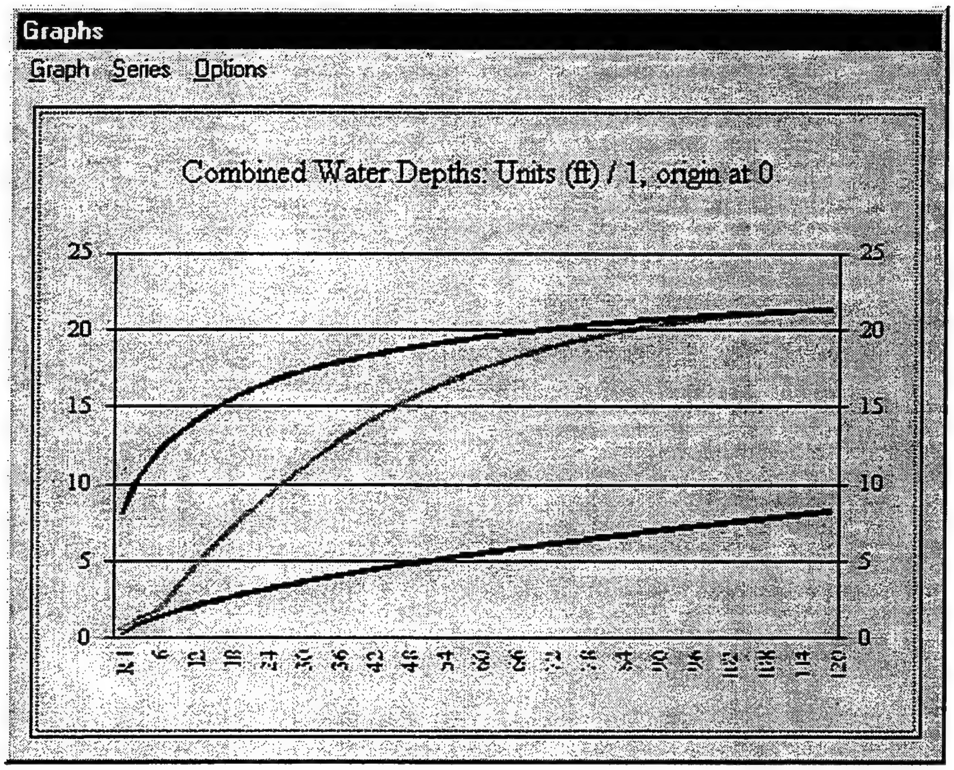

Figure 2.12 Sample Graph Option Screen

III. MODEL VALIDATION

When conducting model validation various calculations of the model were tested separately. First the validation of the flow rates entering the main compartment were tested and compared to U. S. Navy standards. Next the effects of flooding on each of the three hull forms were observed by using various scenarios to demonstrate the progressive flooding and damage control process. The scenarios were used to both validate the model and analyze the hull forms' transient and steady state characteristics of progressive flooding.

A. FLOW RATES VALIDATION

For validation of the flow rates of the flooding in the main compartment the U.S. Naval Ship's Technical Manual (NSTM) [Ref. 6] was used. Table 1 below shows both the NSTM predictions for flow rate and the model observed values with a C_d of 1.0 used as an input parameter and a hole diameter of six inches.

	Delta H (ft)	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**
NSTM	**Q (gal/Min)**	1000	1414	1732	2000	2236	2449	2646	2828	3000
Model	**Q (gal/Min)**	1001	1414	1733	2002	2240	2451	2648	2832	3007
% Diff	**%**	0.09	0.00	0.06	0.01	0.18	0.08	0.08	0.14	0.23

Table 1. Comparison of Model and NSTM flow rates

As can be seen from Table 1 the model accurately calculates the flow rate through hole with a percent difference from the NSTM values of less than 0.25%.

B. FLOODING ANALYSIS

To demonstrate the ability of the model to accurately model progressive flooding and to analyze some of the transient and steady state characteristics of progressive flooding various scenarios were developed and ran. The scenarios will be run on the three different hull forms to compare the similarities and differences.

The barge hull form was first tested as scenario 1. A 120-minute scenario was run using all default parameters. No damage control or dewatering equipment was used because only correct model operation was being evaluated. The main simulation screen at scenario termination is shown in (Figure 3.1). As can be seen from the figure the main compartment had a high flooding level and the secondary compartments also experienced progressive flooding as expected.

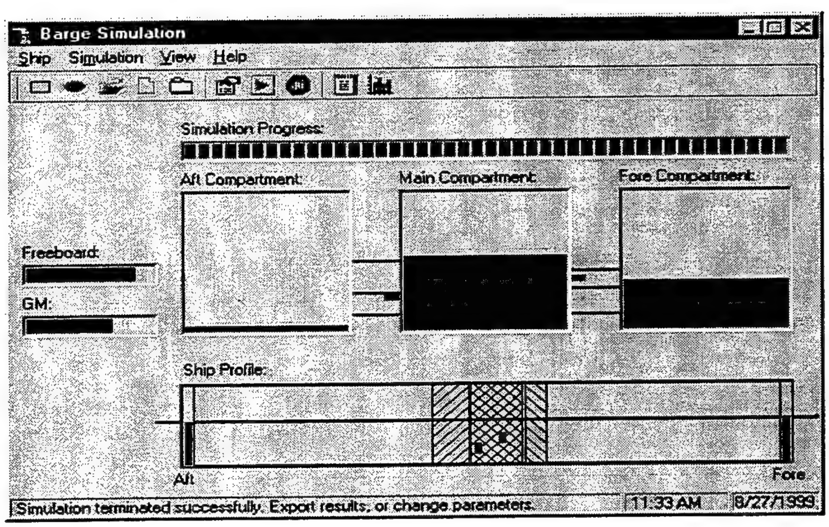

Figure 3.1 Scenario 1 Barge Hull Simulation Screen

Other results must be graphed to further evaluate the results. The flow rates for the main compartment are shown in (Figure 3.2). The graph demonstrates the expected results. Both holes have the correct initial flow rate, which was previously proven, and the flow rate continues to increase due to hull sinkage until the hole becomes submerged.

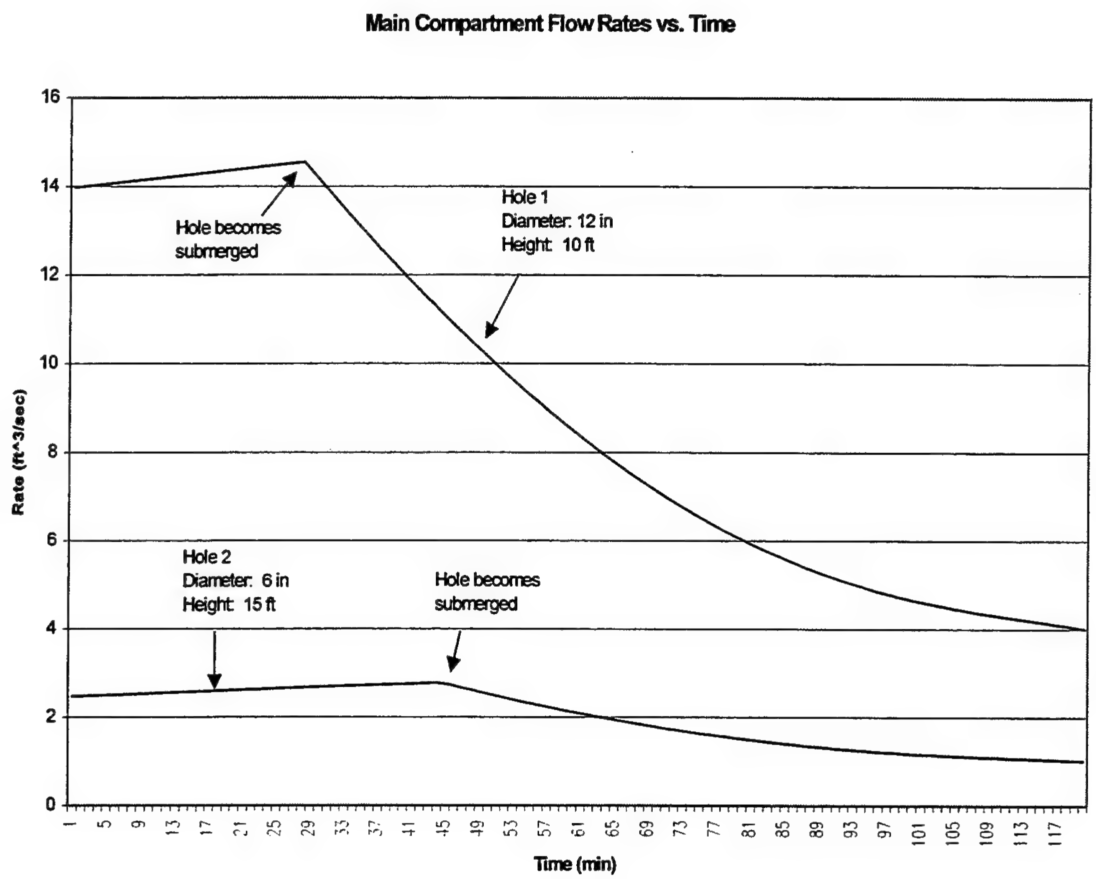

Figure 3.2 Scenario 1 Main Flow Rates vs. Time

As can be seen from (Figure 3.3) the water level in the main compartment increased sharply at the beginning of the simulation. The rate of increase is nearly linear, as expected, because of the nearly constant flow rates until the hole becomes submerged shown in (Figure 3.2). The nearly linear region of the graph ends and the slope begins to

decrease when the main holes become submerged and progressive flooding takes effect. The water levels in the fore and aft compartments indicate the occurrence of progressive flooding. Progressive flooding can not begin until the level of water in the main compartment reaches the height of the secondary fragmentation holes. This occurs at approximately the 20-30 minute range, when the water level in the main compartment exceeds five feet, which is the height of the lowest fragmentation hole. The water level in the forward compartment increases at a faster rate than the aft compartment. This is because the forward compartment contains larger fragmentation holes than the aft compartment.

Shown in (Figure 3.4) are the forward and aft drafts of the barge hull as the simulation progressed. The forward draft increased at a faster rate than the aft indicating a trim by the bow condition. This was expected because the compartments are located forward of midships.

The transverse metacentric height was evaluated in (Figure3.5). The effects of the free surface correction to $\overline{GM}$ can be seen by the sharp decrease. Free surface correction has a drastic correction on the barge hull form because the rectangular surface area of the flooded compartment starts at a large value and remains constant. The Wigley hull form, which is more representative of actual hulls, will not show this trend because the surface area of the flooded compartment starts at a low value and increases as the level of flooding increases.

Effects of flooding that are common to all hull forms, such as: initial increase in hull flow rate due to increasing depth of the hole; decrease in flow rate due to the

submergence of the hole; etc., will not be readdressed in following scenarios unless the effect is specific to the type of hull being addressed.

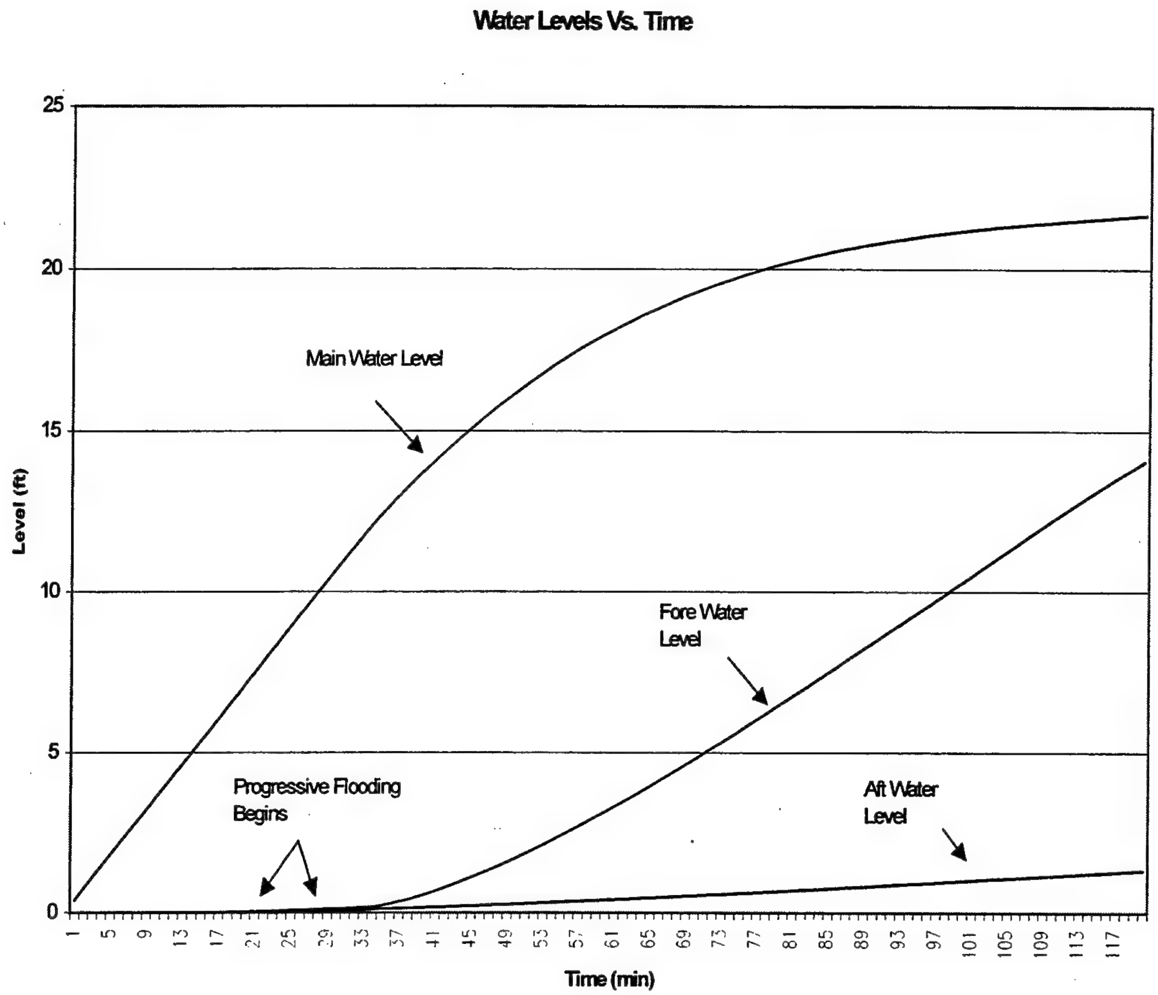

Figure 3.3 Scenario 1 Water Levels vs. Time

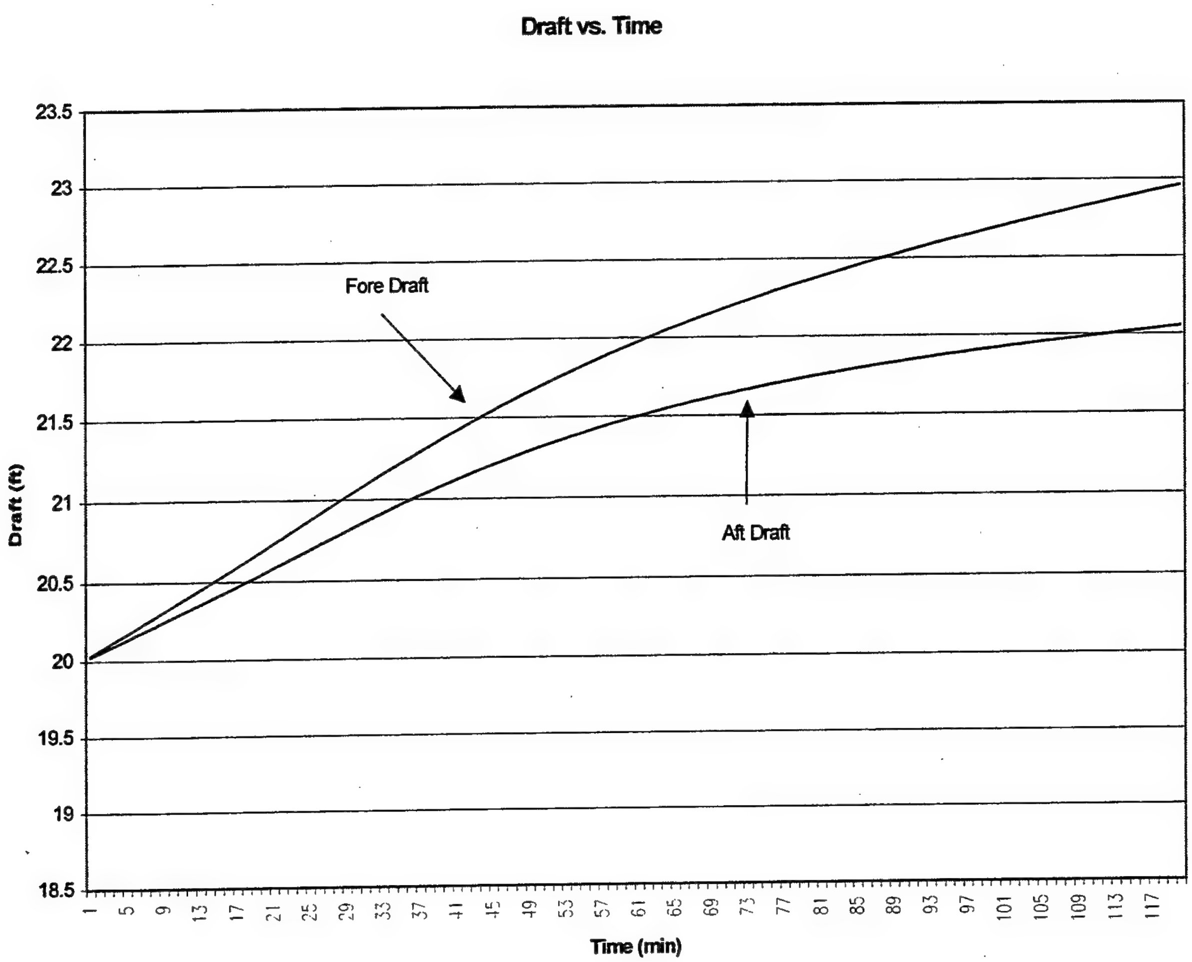

Figure 3.4 Scenario 1 Hull Draft

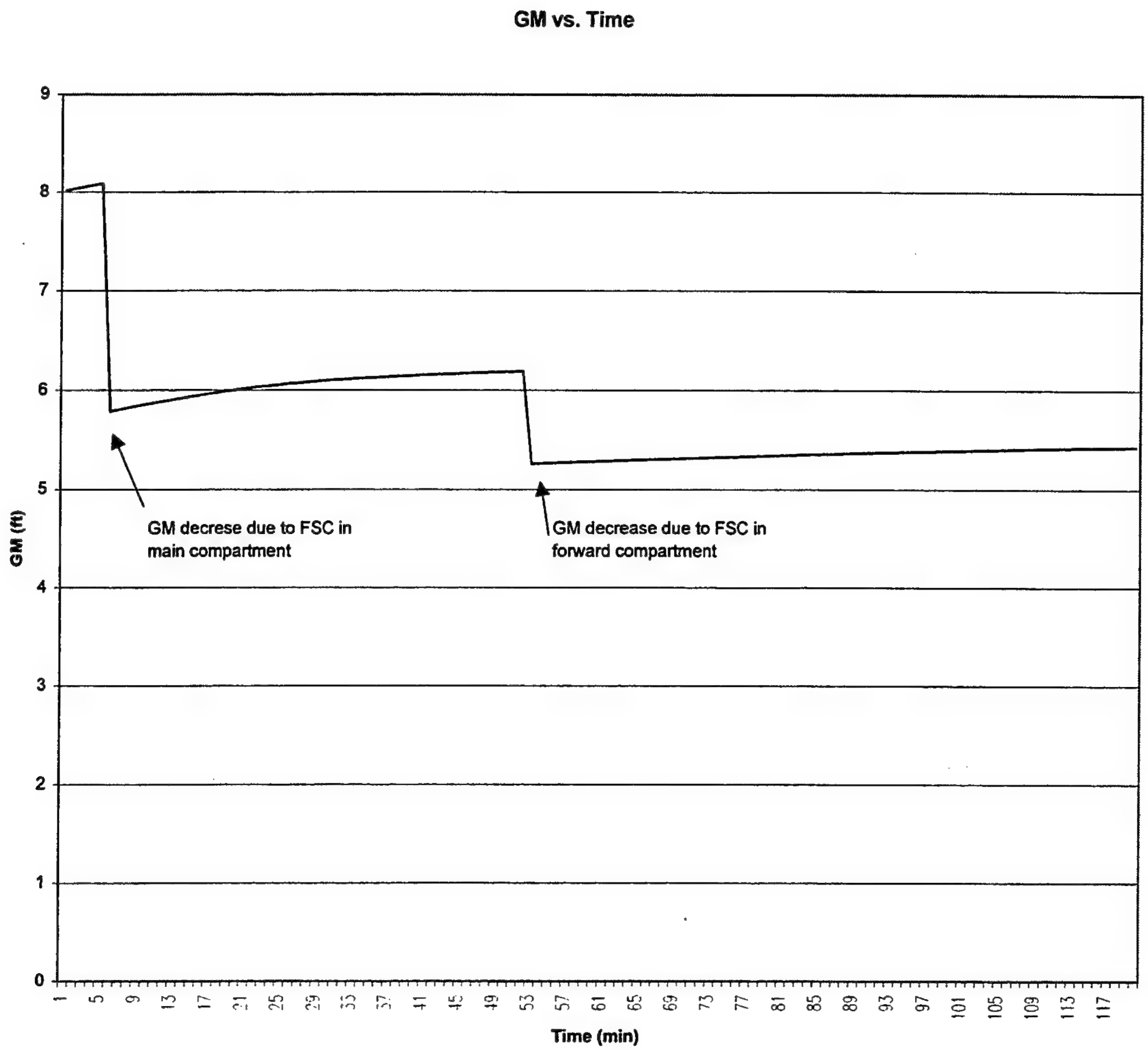

Figure 3.5 Scenario 1 $\overline{GM}$ vs. Time

Scenario 2 was ran to demonstrate flooding effects on the Wigley hull form. The scenario ran with all default parameters for 120 minutes. No dewatering equipment was used. All useful parameters, such as, flooding rates, final draft, final flooding levels, and metacentric height will be shown so that a comparison with the user supplied data hull form can be made in scenario 3. The main simulation screen at scenario termination is

shown in (Figure 3.6). As can be seen from the figure the main compartment had a high flooding level and the secondary compartments experienced progressive flooding as previously demonstrated by the barge hull form.

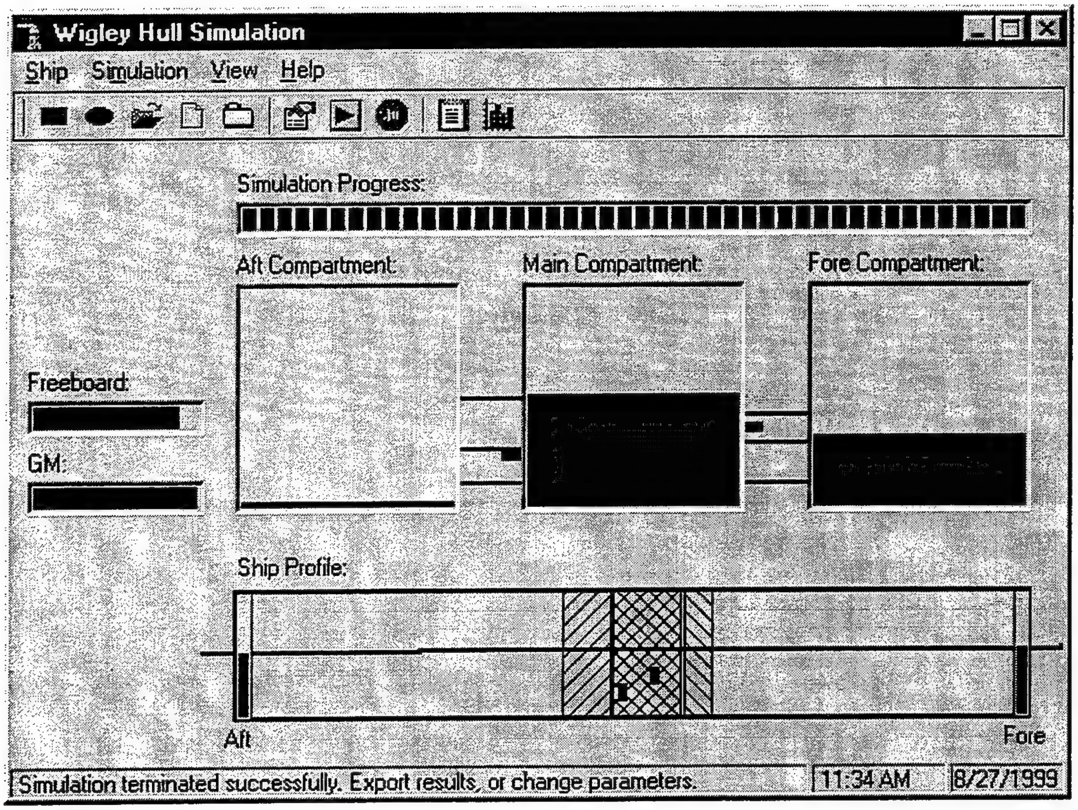

Figure 3.6 Scenario 2 Wigley Hull Simulation Screen

As shown in (Figure 3.7) the water level in the main compartment quickly reach an equilibrium level similar to the barge followed by progressive flooding to the fore and aft compartments. There are two notable differences between the flooding levels in the barge and the Wigley hull form. First, there is a high initial flooding level in the main compartment. This occurs because the Euler ODE solver calculates the level of water in each compartment from the following equation

$$h = h_0 + dt\left(\frac{Q}{A}\right), \tag{35}$$

where h is water height, dt is the time step, Q is the flow rate, and A is the compartment surface area. The surface area of the Wigley hull is zero when the water level is zero and increases as water level increases. This makes the initial water level high but has no effect on the proper program operation. This occurrence can be corrected by using a smaller time step. Second, the water levels in the main and fore compartments reach equilibrium unlike the barge hull form. This can also be attributed to the small initial compartment surface areas.

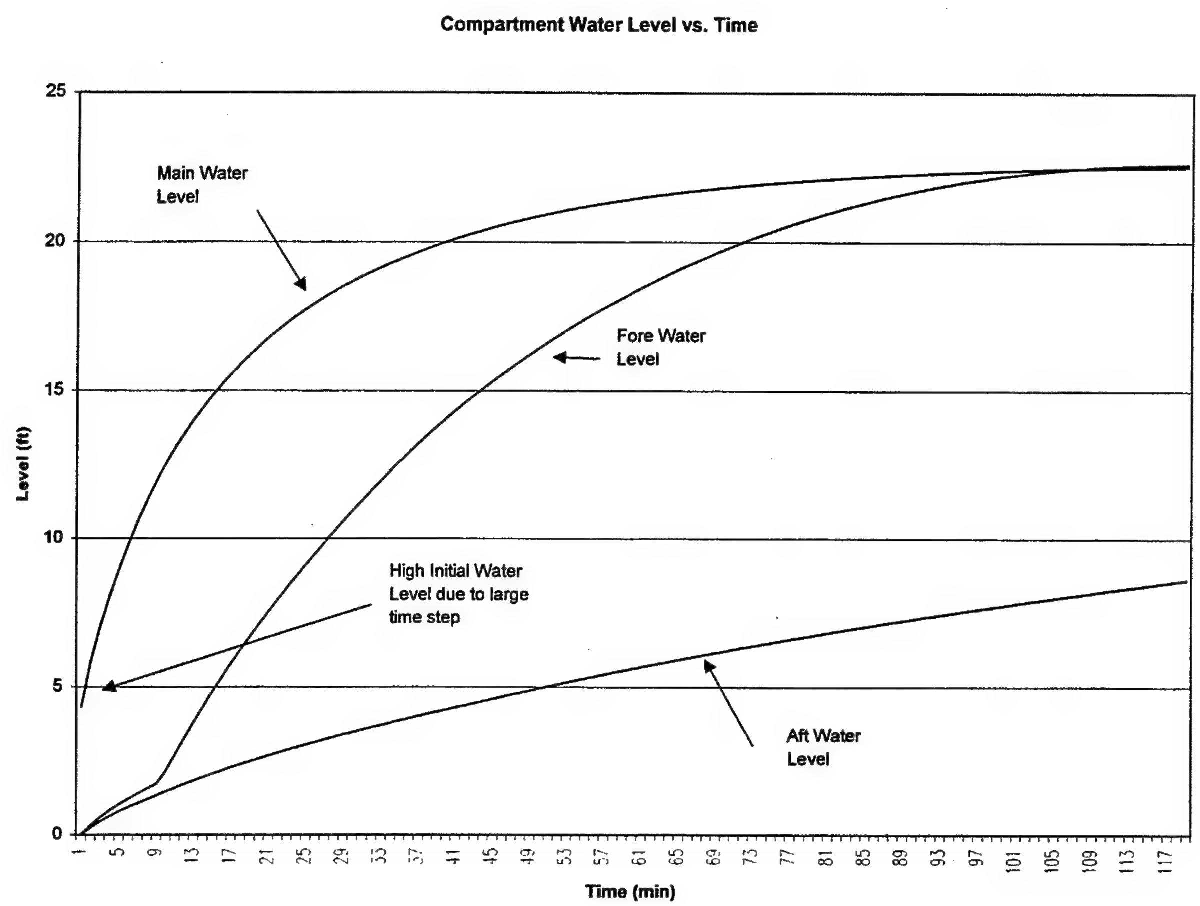

Figure 3.7 Scenario 2 Water Levels vs. Time

The $\overline{GM}$ is shown in (Figure 3.8). The plot shows a steady decrease unlike the sharp decrease experienced in scenario 1. The gradual decrease is due to the free surface correction. The free surface correction did not have as large an impact as scenario 1 because, unlike the barge, the surface area in the Wigley hull was not large at low water levels.

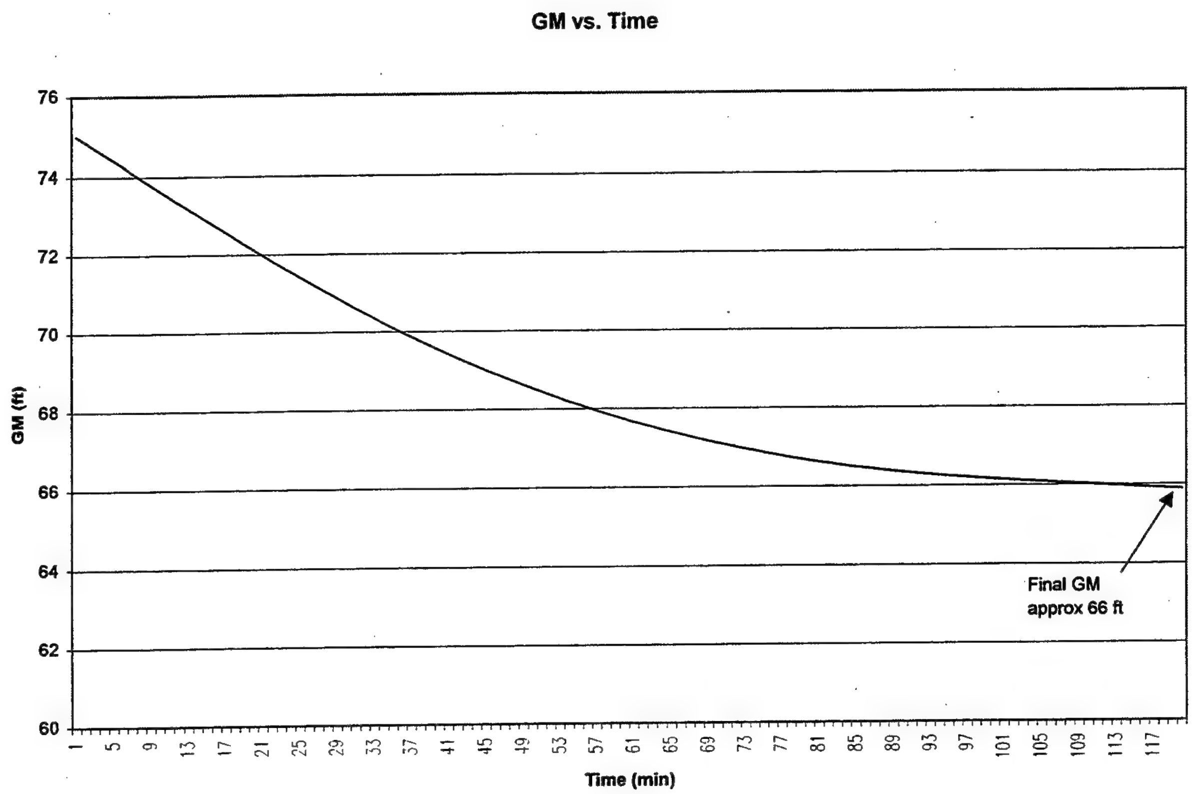

Figure 3.8 Scenario 2 $\overline{GM}$ vs. Time

Scenario 3 was run on the user supplied hull form using the data generated by the Matlab files in (Appendix A). The purpose of this scenario was to test the accuracy of the calculations using a user supplied hull form and compare the results to scenario 2. As

expected scenario 3 showed the same trends as previously discussed in scenario 2. Table 2 lists the tabulated results of scenarios 2 and 3, along with the percent difference.

	FWD Draft	AFT Draft	Main Comp Level	Fwd Comp Level	Aft Comp Level	Final GM
Scenario 2	23.24	21.94	22.57	22.65	9.20	65
Scenario 3	23.34	21.80	22.55	22.65	8.90	64
% Diff	0.43%	0.64%	0.09%	0.00%	3.26%	1.54%

Table 2. Comparison of Scenario 1 and Scenario 2 Results

Relatively low percent differences were encountered in all the tabulated results with the highest error being the water level in the aft compartment.

Scenario 4 was ran to demonstrate the effects of hole plugging and dewatering while running a simulation on the Wigley hull form. A Wigley hull with default dimensions was given standard battle damage as experienced in scenario 2. All pumps were activated, but were not started until flooding progressed. Two 3,000 GPM pumps were in the main compartment and two 2,000 GPM pumps were placed in each the forward and aft compartment. The water heights in each compartment, along with pump activation and hole clogging times, are shown in (Figure 3.9).

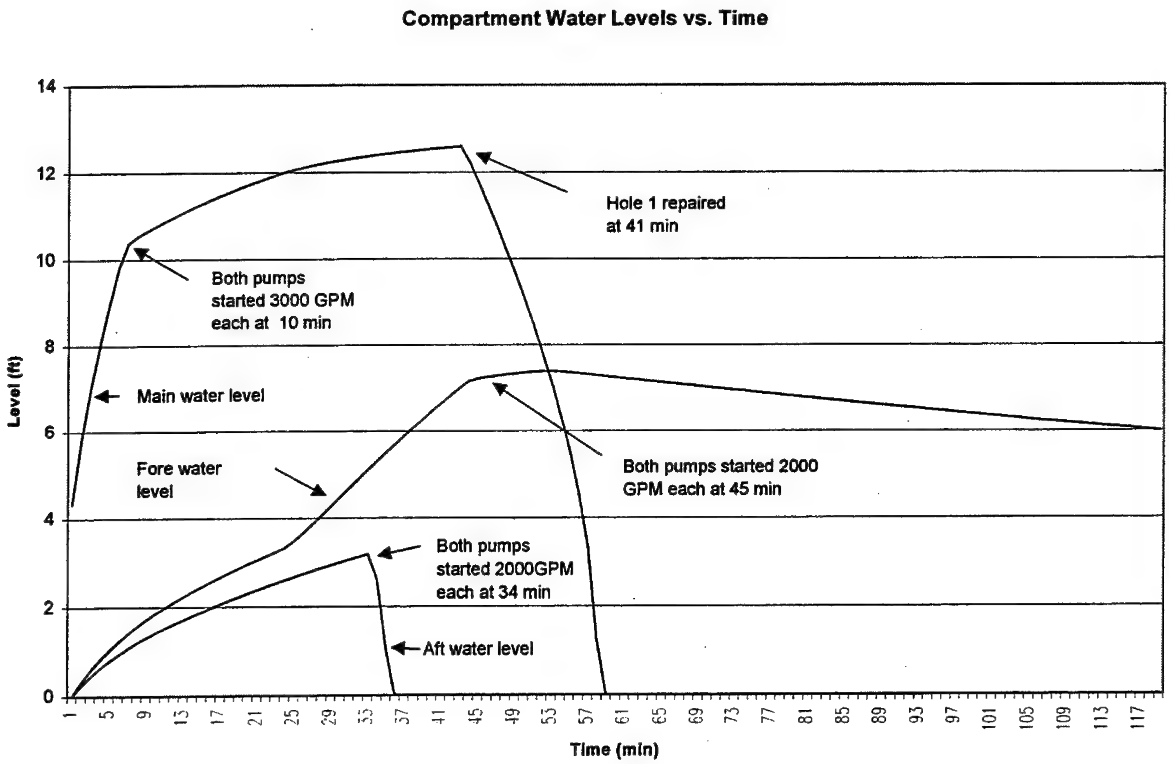

Figure 3.9 Scenario 4 Water Height vs. Time

The slopes of the water level lines in each compartment decreases when each pump is activated as expected. The times of activation are indicated on the graph. The water level in the main compartment begins to decrease when the hole is plugged. It should be noted that the initial water level in the main compartment was lower than scenario 2 because a smaller time step was used. The flow rates for holes in the main compartment are shown in (Figure3.10). The flow rates are shown to demonstrate the decrease when hole 1 is plugged at 41 min. The effects on $\overline{GM}$ are shown in (Figure 3.11). $\overline{GM}$ decreases as flooding progresses then begins to increase while dewatering is being conducted as expected.

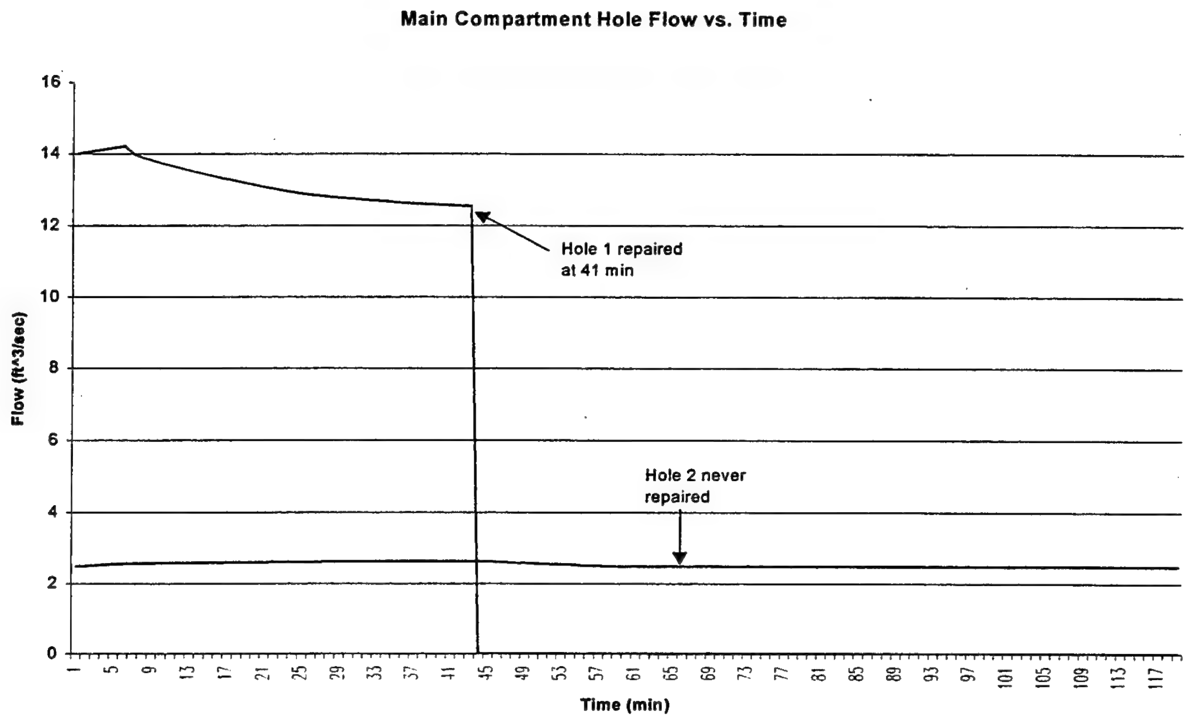

Figure 3.10 Scenario 4 Flow Rates vs. Time

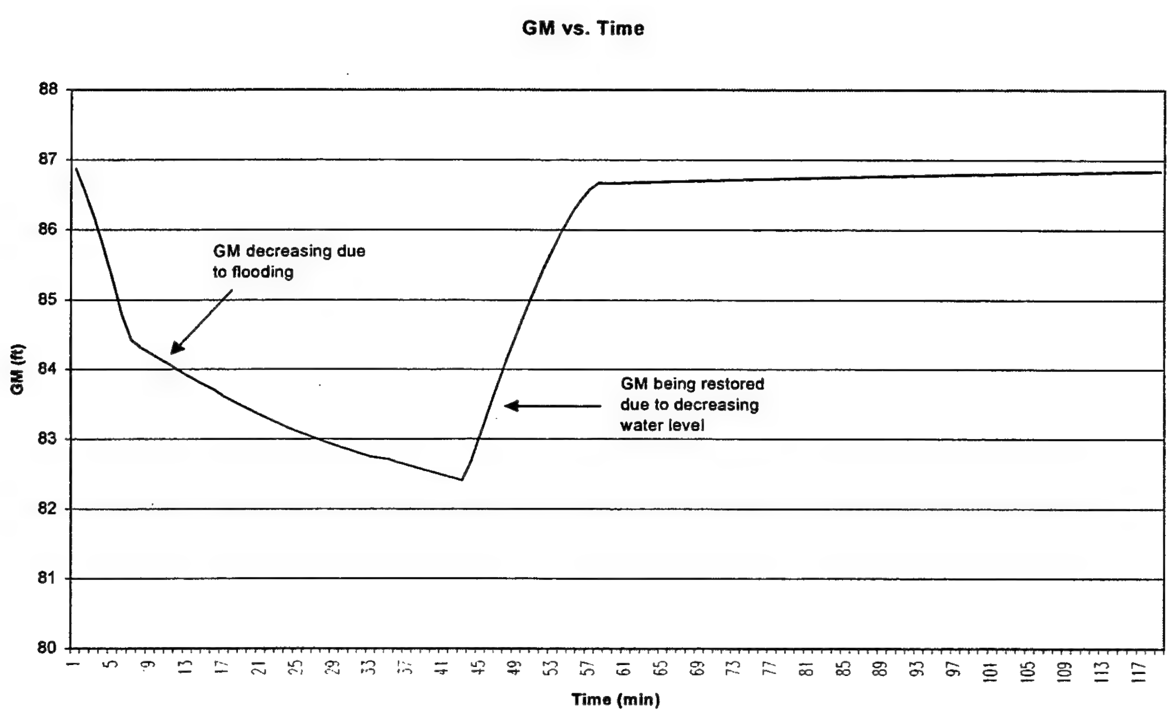

Figure 3.11 Scenario 4 $\overline{GM}$ vs. Time

IV. CONCLUCIONS

This thesis has successfully developed a progressive flooding model using the Visual Basic programming language. This model can be used as a design tool to aid the engineer in stability verifications following battle damage with progressive flooding. The engineer can conduct real time scenarios using the installed dewatering systems or damage control hole plugging techniques to better evaluate any hull form.

Based upon the results discussed in the preceding scenarios the following conclusions are drawn:

1. This model can be used as a design tool to evaluate progressive flooding. The engineer can conduct real time scenarios to verify ship stability and survivability.
2. The user can adapt the model to any hull form and conduct scenarios on any compartment in the hull.
3. Vital Naval architectural parameters, such as free surface effects and internal tank trim are included in the calculations to give more realistic results.
4. The user can use multiple pumping combinations and repair or plug holes to aid in the damage control process.

V. RECOMMENDATIONS

Because this model was developed from ground zero and due to time scope limitations some features of this design tool are still undeveloped. Some of the areas for future development are:

1. Conduct further testing with an actual data supplied hull form with known stability parameters and compare the results.
2. Expand the dewatering feature of the model to include logic controlled pumping.
2. Expand the model to include longitudinal bulkheads so that transverse stability criterion, such as list can be included in the simulation.

APPENDIX A.

HULL AND COMPARTMENT DATA GENERATION PROGRAMS

```
% Tim Spicer
%
% This Matlab program computes various hull characteristics for the
Wigley hull
% form and saves them to a file named 'hulldata'.

clear all

Zl=0.1;               % Temp initial draft
Zh=40;                % Temp final Draft
B=80;                 % Breadth
T=40;                 % Draft
Xl=-200;              % End of ship  (length)
Xh=200;               % begging of ship  (length)
L=400;                % Length of ship
KG=25;

delta=.1;

hulldata = zeros(200,6);

%Hulldata 1 = draft
%Hulldata 2 = volume
%Hulldata 3 = TPI
%Hulldata 4 = KB
%Hulldata 5 = BM
%Hulldata 6 = BML

A = 4/L^2;
Temp = Xh-(A*Xh^3)+((3*A^2*(Xh)^5)/5)-((A^3*(Xh)^7)/7)-((Xl)-
(A*Xl^3)+((3*A^2*(Xl)^5)/5)-((A^3*(Xl)^7)/7));

i = 1;

for z=Zl:delta:Zh
   hulldata(i,1) = z;
   hulldata(i,2) = B*(((z^2)/T)-((z^3)/(3*T^2)))*((Xh-Xl)-
((4/3)*(((Xh^3)/L^2)-((Xl^3)/L^2))));
   hulldata(i,3) = (2*(B/2)*(1-((T-(z))/T)^2)*(Xh-Xl-(4/3)*(Xh^3/L^2-
(Xl^3/L^2))))/420;
   hulldata(i,4) = (2*z^3/(3*T)-z^4/(4*T^2))/(z^2/T-z^3/(3*T^2));
   hulldata(i,5) = ((1/3)*B^3*(1-(T-z)^2/T^2)^3*(Temp))/hulldata(i,2);
   hulldata(i,6) = (B*(1-((T-z)^2/T^2))*((L/2)^3/3-(-L/2)^3/3-
(4/(5*L^2))*((L/2)^5-(-L/2)^5)))/hulldata(i,2);
      i=i+1;
end

save hulldata hulldata -ASCII;
```

```
% Tim Spicer
%
% This program computes various characteristics for the fwd compartment
of
% the Wigley hull form.

clear all

Zl=0.1;                 % Temp initial draft
Zh=40;                  % Temp final Draft
B=80;                   % Breadth
T=40;                   % Draft
Xl=25;                 % End of compartment      (length)
Xh=40;                  % begging of compartment  (length)
L=400;                  % Length of ship
KG=25;


delta=.1;

fwddata = zeros(200,7);

%fwddata 1 = draft
%fwddata 2 = volume
%fwddata 3 = zcoord
%fwddata 4 = It
%fwddata 5 = Il
%fwddata 6 = Area
%fwddata 7 = xcoord

A = 4/L^2;
Temp = Xh-(A*Xh^3)+((3*A^2*(Xh)^5)/5)-((A^3*(Xh)^7)/7)-((Xl)-
(A*Xl^3)+((3*A^2*(Xl)^5)/5)-((A^3*(Xl)^7)/7));

i = 1;

for z=Zl:delta:Zh
   fwddata(i,1) = z;
   fwddata(i,2) = B*(((z^2)/T)-((z^3)/(3*T^2)))*((Xh-Xl)-
((4/3)*(((Xh^3)/L^2)-((Xl^3)/L^2))));
   fwddata(i,3) = B*((((2*z^3)/(3*T))-(z^4/(4*T^2)))*(Xh-Xl-
(4/(3*L^2))*(Xh^3-Xl^3))/(fwddata(i,2)));
   fwddata(i,4) = ((1/3)*B^3*(1-(T-z)^2/T^2)^3*(Xh-
(A*Xh^3)+((3*A^2*(Xh)^5)/5)-((A^3*(Xh)^7)/7)-((Xl)-
(A*Xl^3)+((3*A^2*(Xl)^5)/5)-((A^3*(Xl)^7)/7))));
   fwddata(i,5) = (B*(1-((T-z)^2/T^2))*(Xh^3/3-Xl^3/3-
(4/(5*L^2))*(Xh^5-Xl^5)));
   fwddata(i,6) = 2*(B/2)*(1-((T-(z))/T)^2)*(Xh-Xl-(4/3)*(Xh^3/L^2-
(Xl^3/L^2)));
   fwddata(i,7) = (((Xh^2-Xl^2)/2)-(Xh^4-Xl^4)/(L^2))/((Xh-Xl)-4*(Xh^3-
Xl^3)/(3*(L^2)));
   i=i+1;

   i=i+1;
end

save fwddata fwddata -ASCII;
```

```
% Tim Spicer
%
% This program computes various characteristics for the main
compartment of
% the Wigley hull form.

clear all

Zl=0.1;                 % Temp initial draft
Zh=40;                  % Temp final Draft
B=80;                   % Breadth
T=40;                   % Draft
Xl=-10;                 % End of compartment        (length)
Xh=25;                  % begging of compartment   (length)
L=400;                  % Length of ship
KG=25;


delta=.1;

maindata = zeros(200,7);

%maindata 1 = draft
%maindata 2 = volume
%maindata 3 = zcoord
%maindata 4 = It
%maindata 5 = Il
%maindata 6 = Area
%maindata 7 = xcoord

A = 4/L^2;
Temp = Xh-(A*Xh^3)+((3*A^2*(Xh)^5)/5)-((A^3*(Xh)^7)/7)-((Xl)-
(A*Xl^3)+((3*A^2*(Xl)^5)/5)-((A^3*(Xl)^7)/7));

i = 1;

for z=Zl:delta:Zh
   maindata(i,1) = z;
   maindata(i,2) = B*(((z^2)/T)-((z^3)/(3*T^2)))*((Xh-Xl)-
((4/3)*(((Xh^3)/L^2)-((Xl^3)/L^2))));
   maindata(i,3) = B*((((2*z^3)/(3*T))-(z^4/(4*T^2)))*(Xh-Xl-
(4/(3*L^2))*(Xh^3-Xl^3))/(maindata(i,2)));
   maindata(i,4) = ((1/3)*B^3*(1-(T-z)^2/T^2)^3*(Xh-
(A*Xh^3)+((3*A^2*(Xh)^5)/5)-((A^3*(Xh)^7)/7)-((Xl)-
(A*Xl^3)+((3*A^2*(Xl)^5)/5)-((A^3*(Xl)^7)/7))));
   maindata(i,5) = (B*(1-((T-z)^2/T^2))*(Xh^3/3-Xl^3/3-
(4/(5*L^2))*(Xh^5-Xl^5)));
   maindata(i,6) = 2*(B/2)*(1-((T-(z))/T)^2)*(Xh-Xl-(4/3)*(Xh^3/L^2-
(Xl^3/L^2)));
   maindata(i,7) = (((Xh^2-Xl^2)/2)-(Xh^4-Xl^4)/(L^2))/((Xh-Xl)-
4*(Xh^3-Xl^3)/(3*(L^2)));
   i=i+1;

   i=i+1;
end

save maindata maindata -ASCII;
```

```
% Tim Spicer
%
% This program computes various characteristics for the aft compartment
of
% the Wigley hull form.



clear all

Zl=0.1;              % Temp initial draft
Zh=40;               % Temp final Draft
B=80;                % Breadth
T=40;                % Draft
Xl=-35;              % End of compartment       (length)
Xh=-10;               % begging of compartment  (length)
L=400;               % Length of ship
KG=25;


delta=.1;

aftdata = zeros(200,7);

%aftdata 1 = draft
%aftdata 2 = volume
%aftdata 3 = zcoord
%aftdata 4 = It
%aftdata 5 = Il
%aftdata 6 = Area
%aftdata 7 = xcoord

A = 4/L^2;
Temp = Xh-(A*Xh^3)+((3*A^2*(Xh)^5)/5)-((A^3*(Xh)^7)/7)-((Xl)-
(A*Xl^3)+((3*A^2*(Xl)^5)/5)-((A^3*(Xl)^7)/7));

i = 1;

for z=Zl:delta:Zh
   aftdata(i,1) = z;
   aftdata(i,2) = B*(((z^2)/T)-((z^3)/(3*T^2)))*((Xh-Xl)-
((4/3)*(((Xh^3)/L^2)-((Xl^3)/L^2))));
   aftdata(i,3) = B*((((2*z^3)/(3*T))-(z^4/(4*T^2)))*(Xh-Xl-
(4/(3*L^2))*(Xh^3-Xl^3))/(aftdata(i,2)));
   aftdata(i,4) = ((1/3)*B^3*(1-(T-z)^2/T^2)^3*(Xh-
(A*Xh^3)+((3*A^2*(Xh)^5)/5)-((A^3*(Xh)^7)/7)-((Xl)-
(A*Xl^3)+((3*A^2*(Xl)^5)/5)-((A^3*(Xl)^7)/7))));
   aftdata(i,5) = (B*(1-((T-z)^2/T^2))*(Xh^3/3-Xl^3/3-
(4/(5*L^2))*(Xh^5-Xl^5)));
   aftdata(i,6) = 2*(B/2)*(1-((T-(z))/T)^2)*(Xh-Xl-(4/3)*(Xh^3/L^2-
(Xl^3/L^2)));
   aftdata(i,7) = (((Xh^2-Xl^2)/2)-(Xh^4-Xl^4)/(L^2))/((Xh-Xl)-4*(Xh^3-
Xl^3)/(3*(L^2)));
   i=i+1;
end
```

save aftdata aftdata -ASCII;

APPENDIX B.

SAMPLE HULL DATA

1.0000000e-001	5.3288889e+000	2.5365079e-001	6.6659716e-002	7.2929689e-001	1.5993328e+005
2.0000000e-001	2.1297778e+001	5.0666667e-001	1.3330551e-001	1.4543370e+000	7.9933222e+004
3.0000000e-001	4.7880000e+001	7.5904762e-001	1.9993734e-001	2.1751303e+000	5.3266500e+004
4.0000000e-001	8.5048889e+001	1.0107937e+000	2.6655518e-001	2.8916866e+000	3.9933110e+004
5.0000000e-001	1.3277778e+002	1.2619048e+000	3.3315900e-001	3.6040158e+000	3.1933054e+004
6.0000000e-001	1.9104000e+002	1.5123810e+000	3.9974874e-001	4.3121279e+000	2.6599665e+004
7.0000000e-001	2.5980889e+002	1.7622222e+000	4.6632439e-001	5.0160328e+000	2.2790085e+004
8.0000000e-001	3.3905778e+002	2.0114286e+000	5.3288591e-001	5.7157402e+000	1.9932886e+004
9.0000000e-001	4.2876000e+002	2.2600000e+000	5.9943325e-001	6.4112602e+000	1.7710607e+004
1.0000000e+000	5.2888889e+002	2.5079365e+000	6.6596639e-001	7.1026026e+000	1.5932773e+004
1.1000000e+000	6.3941778e+002	2.7552381e+000	7.3248528e-001	7.7897774e+000	1.4478171e+004
1.2000000e+000	7.6032000e+002	3.0019048e+000	7.9898990e-001	8.4727943e+000	1.3265993e+004
1.3000000e+000	8.9156889e+002	3.2479365e+000	8.6548020e-001	9.1516634e+000	1.2240296e+004
1.4000000e+000	1.0331378e+003	3.4933333e+000	9.3195616e-001	9.8263944e+000	1.1361118e+004
1.5000000e+000	1.1850000e+003	3.7380952e+000	9.9841772e-001	1.0496997e+001	1.0599156e+004
1.6000000e+000	1.3471289e+003	3.9822222e+000	1.0648649e+000	1.1163482e+001	9.9324324e+003
1.7000000e+000	1.5194978e+003	4.2257143e+000	1.1312975e+000	1.1825858e+001	9.3441400e+003
1.8000000e+000	1.7020800e+003	4.4685714e+000	1.1977157e+000	1.2484136e+001	8.8212070e+003
1.9000000e+000	1.8948489e+003	4.7107937e+000	1.2641194e+000	1.3138325e+001	8.3533134e+003
2.0000000e+000	2.0977778e+003	4.9523810e+000	1.3305085e+000	1.3788436e+001	7.9322034e+003
2.1000000e+000	2.3108400e+003	5.1933333e+000	1.3968830e+000	1.4434478e+001	7.5511935e+003
2.2000000e+000	2.5340089e+003	5.4336508e+000	1.4632428e+000	1.5076460e+001	7.2048156e+003
2.3000000e+000	2.7672578e+003	5.6733333e+000	1.5295879e+000	1.5714394e+001	6.8885523e+003
2.4000000e+000	3.0105600e+003	5.9123810e+000	1.5959184e+000	1.6348288e+001	6.5986395e+003
2.5000000e+000	3.2638889e+003	6.1507937e+000	1.6622340e+000	1.6978153e+001	6.3319149e+003
2.6000000e+000	3.5272178e+003	6.3885714e+000	1.7285349e+000	1.7603999e+001	6.0857031e+003
2.7000000e+000	3.8005200e+003	6.6257143e+000	1.7948210e+000	1.8225835e+001	5.8577247e+003
2.8000000e+000	4.0837689e+003	6.8622222e+000	1.8610922e+000	1.8843672e+001	5.6460263e+003
2.9000000e+000	4.3769378e+003	7.0980952e+000	1.9273484e+000	1.9457518e+001	5.4489237e+003
3.0000000e+000	4.6800000e+003	7.3333333e+000	1.9935897e+000	2.0067385e+001	5.2649573e+003
3.1000000e+000	4.9929289e+003	7.5679365e+000	2.0598161e+000	2.0673281e+001	5.0928558e+003
3.2000000e+000	5.3156978e+003	7.8019048e+000	2.1260274e+000	2.1275217e+001	4.9315068e+003
3.3000000e+000	5.6482800e+003	8.0352381e+000	2.1922237e+000	2.1873203e+001	4.7799330e+003
3.4000000e+000	5.9906489e+003	8.2679365e+000	2.2584048e+000	2.2467248e+001	4.6372717e+003
3.5000000e+000	6.3427778e+003	8.5000000e+000	2.3245708e+000	2.3057363e+001	4.5027590e+003
3.6000000e+000	6.7046400e+003	8.7314286e+000	2.3907216e+000	2.3643556e+001	4.3757159e+003
3.7000000e+000	7.0762089e+003	8.9622222e+000	2.4568573e+000	2.4225839e+001	4.2555367e+003
3.8000000e+000	7.4574578e+003	9.1923810e+000	2.5229776e+000	2.4804221e+001	4.1416795e+003
3.9000000e+000	7.8483600e+003	9.4219048e+000	2.5890827e+000	2.5378711e+001	4.0336580e+003
4.0000000e+000	8.2488889e+003	9.6507937e+000	2.6551724e+000	2.5949320e+001	3.9310345e+003
4.1000000e+000	8.6590178e+003	9.8790476e+000	2.7212468e+000	2.6516058e+001	3.8334140e+003
4.2000000e+000	9.0787200e+003	1.0106667e+001	2.7873057e+000	2.7078933e+001	3.7404392e+003
4.3000000e+000	9.5079689e+003	1.0333651e+001	2.8533492e+000	2.7637957e+001	3.6517859e+003
4.4000000e+000	9.9467378e+003	1.0560000e+001	2.9193772e+000	2.8193139e+001	3.5671595e+003
4.5000000e+000	1.0395000e+004	1.0785714e+001	2.9853896e+000	2.8744489e+001	3.4862915e+003

APPENDIX C.

SAMPLE COMPARTMENT DATA

1.0000000e-001	4.9260998e-001	3.3329858e-002	5.0950090e-001	5.4716415e+003	9.8480911e+000	-2.2440577e+001
2.0000000e-001	1.9687965e+000	6.6652755e-002	4.0607222e+000	1.0929587e+004	1.9671531e+001	-2.2440577e+001
3.0000000e-001	4.4260945e+000	9.9968672e-002	1.3653480e+001	1.6373836e+004	2.9470320e+001	-2.2440577e+001
4.0000000e-001	7.8620389e+000	1.3327759e-001	3.2242135e+001	2.1804389e+004	3.9244458e+001	-2.2440577e+001
5.0000000e-001	1.2274164e+001	1.6657950e-001	6.2735883e+001	2.7221245e+004	4.8993945e+001	-2.2440577e+001
6.0000000e-001	1.7660006e+001	1.9987437e-001	1.0799903e+002	3.2624405e+004	5.8718781e+001	-2.2440577e+001
7.0000000e-001	2.4017099e+001	2.3316220e-001	1.7085130e+002	3.8013870e+004	6.8418966e+001	-2.2440577e+001
8.0000000e-001	3.1342978e+001	2.6644295e-001	2.5406809e+002	4.3389637e+004	7.8094500e+001	-2.2440577e+001
9.0000000e-001	3.9635177e+001	2.9971662e-001	3.6038076e+002	4.8751709e+004	8.7745383e+001	-2.2440577e+001
1.0000000e+000	4.8891233e+001	3.3298319e-001	4.9247693e+002	5.4100085e+004	9.7371615e+001	-2.2440577e+001
1.1000000e+000	5.9108679e+001	3.6624264e-001	6.5300075e+002	5.9434764e+004	1.0697320e+002	-2.2440577e+001
1.2000000e+000	7.0285050e+001	3.9949495e-001	8.4455319e+002	6.4755747e+004	1.1655013e+002	-2.2440577e+001
1.3000000e+000	8.2417882e+001	4.3274010e-001	1.0696923e+003	7.0063034e+004	1.2610240e+002	-2.2440577e+001
1.4000000e+000	9.5504709e+001	4.6597808e-001	1.3309335e+003	7.5356624e+004	1.3563003e+002	-2.2440577e+001
1.5000000e+000	1.0954307e+002	4.9920886e-001	1.6307499e+003	8.0636519e+004	1.4513301e+002	-2.2440577e+001
1.6000000e+000	1.2453049e+002	5.3243243e-001	1.9715725e+003	8.5902717e+004	1.5461133e+002	-2.2440577e+001
1.7000000e+000	1.4046451e+002	5.6564877e-001	2.3557905e+003	9.1155219e+004	1.6406501e+002	-2.2440577e+001
1.8000000e+000	1.5734267e+002	5.9885787e-001	2.7857516e+003	9.6394024e+004	1.7349403e+002	-2.2440577e+001
1.9000000e+000	1.7516250e+002	6.3205970e-001	3.2637623e+003	1.0161913e+005	1.8289840e+002	-2.2440577e+001
2.0000000e+000	1.9392153e+002	6.6525424e-001	3.7920880e+003	1.0683055e+005	1.9227813e+002	-2.2440577e+001
2.1000000e+000	2.1361730e+002	6.9844148e-001	4.3729536e+003	1.1202826e+005	2.0163320e+002	-2.2440577e+001
2.2000000e+000	2.3424735e+002	7.3162139e-001	5.0085435e+003	1.1721228e+005	2.1096361e+002	-2.2440577e+001
2.3000000e+000	2.5580920e+002	7.6479397e-001	5.7010018e+003	1.2238261e+005	2.2026938e+002	-2.2440577e+001
2.4000000e+000	2.7830040e+002	7.9795918e-001	6.4524330e+003	1.2753924e+005	2.2955050e+002	-2.2440577e+001
2.5000000e+000	3.0171848e+002	8.3111702e-001	7.2649018e+003	1.3268217e+005	2.3880697e+002	-2.2440577e+001
2.6000000e+000	3.2606097e+002	8.6426746e-001	8.1404336e+003	1.3781141e+005	2.4803878e+002	-2.2440577e+001
2.7000000e+000	3.5132541e+002	8.9741049e-001	9.0810149e+003	1.4292695e+005	2.5724595e+002	-2.2440577e+001
2.8000000e+000	3.7750934e+002	9.3054608e-001	1.0088593e+004	1.4802879e+005	2.6642846e+002	-2.2440577e+001
2.9000000e+000	4.0461028e+002	9.6367421e-001	1.1165078e+004	1.5311694e+005	2.7558632e+002	-2.2440577e+001
3.0000000e+000	4.3262578e+002	9.9679487e-001	1.2312339e+004	1.5819139e+005	2.8471953e+002	-2.2440577e+001
3.1000000e+000	4.6155337e+002	1.0299080e+000	1.3532210e+004	1.6325214e+005	2.9382809e+002	-2.2440577e+001
3.2000000e+000	4.9139058e+002	1.0630137e+000	1.4826485e+004	1.6829920e+005	3.0291200e+002	-2.2440577e+001
3.3000000e+000	5.2213495e+002	1.0961118e+000	1.6196923e+004	1.7333256e+005	3.1197126e+002	-2.2440577e+001
3.4000000e+000	5.5378401e+002	1.1292024e+000	1.7645244e+004	1.7835223e+005	3.2100586e+002	-2.2440577e+001
3.5000000e+000	5.8633530e+002	1.1622854e+000	1.9173132e+004	1.8335820e+005	3.3001582e+002	-2.2440577e+001
3.6000000e+000	6.1978635e+002	1.1953608e+000	2.0782232e+004	1.8835047e+005	3.3900113e+002	-2.2440577e+001
3.7000000e+000	6.5413470e+002	1.2284286e+000	2.2474157e+004	1.9332905e+005	3.4796178e+002	-2.2440577e+001
3.8000000e+000	6.8937788e+002	1.2614888e+000	2.4250479e+004	1.9829393e+005	3.5689778e+002	-2.2440577e+001
3.9000000e+000	7.2551344e+002	1.2945413e+000	2.6112738e+004	2.0324512e+005	3.6580913e+002	-2.2440577e+001
4.0000000e+000	7.6253889e+002	1.3275862e+000	2.8062436e+004	2.0818260e+005	3.7469583e+002	-2.2440577e+001
4.1000000e+000	8.0045178e+002	1.3606234e+000	3.0101041e+004	2.1310640e+005	3.8355788e+002	-2.2440577e+001
4.2000000e+000	8.3924964e+002	1.3936528e+000	3.2229985e+004	2.1801649e+005	3.9239528e+002	-2.2440577e+001
4.3000000e+000	8.7893001e+002	1.4266746e+000	3.4450666e+004	2.2291289e+005	4.0120803e+002	-2.2440577e+001
4.4000000e+000	9.1949043e+002	1.4596886e+000	3.6764446e+004	2.2779560e+005	4.0999612e+002	-2.2440577e+001
4.5000000e+000	9.6092842e+002	1.4926948e+000	3.9172655e+004	2.3266460e+005	4.1875957e+002	-2.2440577e+001

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